The Rustless Wonder

A Study of the Iron Pillar at Delhi

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VIGYAN PRASAR

Published by
Vigyan Prasar
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(Regd. office : Technology Bhawan, New Delhi - 11 0 016)
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The Rustless Wonder: A Study of the Iron Pillar at Delhi
(A publication under Vigyan Prasar Series of Monographs on India's Scientific Heritage)

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Edited By: Narender K. Sehgal
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Coverdesign : Tanudeep

ISBN : 81-7480-015-8

Library of Congress Card No. : 96-902111

Typeset in 12.5/15pt Times New Roman at Vigyan Prasar
by Ganesh Hegde and Sonu Gupta

Printed in India

Apparently ancient India had made great progress in the working of Iron. Near Delhi there towers a great iron pillar which baffles contemporary scientists. They cannot determine the method of manufacture which prevented the iron from oxidation and other atmospheric hazards.

Jawaharlal Nehru (1889-1964)
in *Discovery of India*

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PREFACE

I feel happy and privileged to have this opportunity to launch Vigyan Prasar's Series of Monographs on India's Scientific Heritage with my study of the Iron Pillar at Mehrauli in South Delhi. This famous monument and great tourist attraction is located not far from Vigyan Prasar's office and has been universally acclaimed as among the most impressive technological achievements of ancient India. In fact, it will be no exaggeration to state that this "Rustless Wonder" constitutes the most outstanding human achievement of that period in iron technology.

The Prologue and the first two Chapters of this handy volume are devoted to introducing the subject in proper metallurgical perspective. These also provide all relevant facts and figures about this famous Pillar, as also some valuable information about the inscriptions on it, particularly the earliest and the most important one in Sanskrit. Chapter III deals with the historical and archaeological aspects of the Pillar. While Chapter IV deals with the evolution of Iron Technology, Chapter V highlights the special fabrication technique adopted to raise this tall and heavy monument gradually over a period of time. Chapter VI considers comprehensively and critically the possible reasons for the spectacular and rather baffling corrosion resistance exhibited by this Pillar despite exposure to sun, rain, dust and winds for over fifteen centuries. The Epilogue summarizes the main findings of this study and concludes that there is now very little about the Pillar that has to be labelled as mysterious or has to be imagined.

My grateful thanks are due to Dr. P. Rama Rao, formerly Secretary, Department of Science and Technology, Government

of India, and presently Distinguished Scientist, Defence Research and Development Organization, New Delhi, as also President, Indian Academy of Sciences, for carefully going through the manuscript and offering many valuable suggestions for improving the same.

I am also beholden to Dr. Narender K. Sehgal, Director, and Dr. Subodh Mahanti, Editor-cum-Chief (Publications) of Vigyan Prasar, for their interest and involvement, advice and assistance, in bringing out this first volume in the new 'Monograph Series on India's Scientific Heritage.'

New Delhi **T. R. Anantharaman**
July 10, 1996

Introducing

VIGYAN PRASAR

Vigyan Prasar (VP) was set up by the Department of Science and Technology, Government of India, as an autonomous registered Society in 1989 for taking up large-scale science popularisation tasks. Its broad objectives may be summarised as follows:

- To undertake, aid, promote, guide and coordinate efforts in popularisation of science and inculcation of scientific temper among the people and to increase the knowledge, awareness and interest about science and technology among all segments of the society.

- To provide and promote effective linkages on a continuing basis among various scientific institutions, agencies, educational and academic bodies, laboratories, museums, industry, trade and other organisations for effective exchange and dissemination of S&T information.

- To undertake development of materials — audio, visual, audio-visual and printed —, methods and modes of communication, so as to enable the masses to better underst and, appreciate and comprehend abstract scientific principles and practices.

- To organise research work, courses, workshops, seminars, symposia, training programmes, fairs, exhibitions, film-shows, popular discussions, street plays, quizzes, song-dance-dramas etc., in furtherance of the objectives of the Society.

After its establishment Vigyan Prasar remained dormant for a few years. Only in 1994 some activities could be taken up in right

earnest. One among the first few programmes initiated by Vigyan Prasar was the 'Ready-to-Print' Science Page project. The idea was to prepare a well laid-out newspaper-size page with one or two features and several smaller items on scientific and technological (S&T) developments taking place in India, appropriately supported with photographs, illustrations, graphics etc., and to supply it to newspapers to reproduce as it is. Initially, such pages in Hindi and English were planned for release once a month. Subsequently, a children's page, science pages in other major Indian languages and *a feature packet service were also added. Today, these pages are being carried once or twice a month by more than 30 editions of* some 20 newspapers spread all over the country. In fact, today Vigyan Prasar's are the largest circulated science pages in the country. The combined print order of all these newspapers exceeds 2.5 million copies. These pages have led to fresh demands for enhanced science coverage in other newspapers.

Vigyan Prasar's publications programme is gradually taking shape. A number of important series has been launched; some more are planned. The first major English publication brought out by Vigyan Prasar, viz., "Memoirs of Ruchi Ram Sahni: Pioneer of Science Popularisation in Punjab," under its series on Pioneer Science Popularisers in Pre-Independence India has generated a positive awareness among science communicators and enthused researchers about the need to unearth other such personalities in other parts of the country. Already names of a number of individuals who did pioneering work in the field of science popularisation in pre-independence India have come to light.

Popular science classics written by Great Masters in the past, which have inspired generations of students of science, are no longer seen in the hands of our younger generation. This is not because these books have gone out of context, but because they are no longer available. Vigyan Prasar under its Popular Science Classics series intends to reprint these books and bring them out in low-priced affordable editions so that more and more children can have them. Already two such classics (Michael Faraday's *Chemical History of a Candle* and C.V. Boys' *Soap*

Bubbles And the Forces Which Mould Them) have been brought out and more are on the way.

Inspired by the focal theme for the National Science Day-1995, viz., 'Science for Health', Vigyan Prasar initiated a Health Series. Under it publications on all common diseases, along with possible cures and preventive measures, will be brought out. The first three titles on Sexually Transmitted Diseases, Asthma and Jaundice, have already been released.

Under its series of Monographs on India's Scientific Heritage Vigyan Prasar intends to bring out publications on specific science and technology areas in which India's contributions have stood the test of time, as also have made an impact on modern-day science. The present volume on the Iron Pillar at Delhi is the first to be brought out under this series.

The Total Solar Eclipse of October 24, 1995, provided Vigyan Prasar a rare opportunity to organise a country-wide awareness campaign, aimed at dispelling age-old myths and superstitious beliefs related to eclipses, and to develop among people an urge to learn about their known scientific aspects. Vigyan Prasar jointly with the National Council for Science and Technology Communication (NCSTC) organised a number of activities:

i. Telescope-making workshops for students and teachers.

ii. Development and production of books, a total solar eclipse chart and an activity kit for children.

iii. Production of several video films and their telecast.

Vigyan Prasar conceptualised and implemented a novel idea for ensuring that people did come out and watch the total solar eclipse. It circulated a total solar eclipse pledge. People in thousands from all corners of the country sent in signed pledges. Many individuals and voluntary agencies got these pledges

translated into regional languages on their own and distributed the same in large numbers. All this led to a chain of activities throughout the country. The efforts made by VP, NCSTC and other agencies created a situation where millions of people came out and watched the spectacular event. This was a unique experience and made Vigyan Prasar's name a household word throughout the country.

Under its audio-visual programme, Vigyan Prasar developed a set of video films and several radio programmes on the occasion of the total solar eclipse of 24 October 1995. This event-based effort was enormously satisfying for the VP family and generated a very good response from the public at large.

Vigyan Prasar has recently begun building an Information System called VIPRIS — acronym for Vigyan Prasar Information System — to meet a long-standing demand from different quarters, particularly the science communicators, to establish a repository of background data and information on various aspects of S&T which would be accessible easily. The computerised system would be built on a modular basis, and aim to meet the information needs of science communicators of all kinds.

At this stage, under VIPRIS, we have a fortnightly clippings service, an electronic bulletin board service (BBS), two pages daily on Doordarshan's teletext service and weekly science news on the radio. Several other products and services, including training, development and production of CD-ROMs, generation of data bases on different subject areas etc., are being planned.

Vigyan Prasar has also produced audio-cassette sets of the 108-part radio serial 'Manav Ka Vikas' (jointly produced by the NCSTC and All India Radio) in 18 Indian languages.

This is not all. Vigyan Prasar does many other things. But for now this should suffice.

July 10, 1996

Narender K. Sehgal
Director
Vigyan Prasar

PROLOGUE

Science, technology and engineering have made astonishing strides in numerous directions during the twentieth century. In fact, it would be no exaggeration to state that they dominate our lives and modes of thinking today, as never before in human history. And yet, one cannot overlook the almost unbelievable fact that a systematic, purposeful and large-scale, nay, almost explosive, development of these three highly potent, formidable and interdependent disciplines has taken place on this planet *only* during the last 200 years! For nearly 200,000 years man had used only skin, bone and stone as materials and tools in his day-to-day existence. His interest in metals and his ability to fashion them for different uses i.e., the beginnings of what we presently call metallurgy or the science and technology of metals, go back to just about 10,000 years.

As every present-day school-going student knows, the material world is made up of 92 *naturally* occurring chemical elements, which give rise, on a systematic arrangement, to the famous Periodic Table of elements (see Fig.1). Roughly two-thirds of these elements are metals (the others being non-metals and rare gases) and constitute the foundation for the mighty engineering-cum-technological edifice raised by man during this century. From the cradle to the coffin, all through life, metals give company to man and also enrich his way of living in manifold ways. And yet, the progress in the discovery of the chemical elements, dominated by the species known as metals, has been extremely slow. During the ancient period (1500 B.C. to A.D 1000) and for part of the medieval period (A. D. 1000 to A.D. 1750), indeed up to A.D. 1500 i.e., till about 500 years ago, the human family seems to have known only eight metals, viz.,

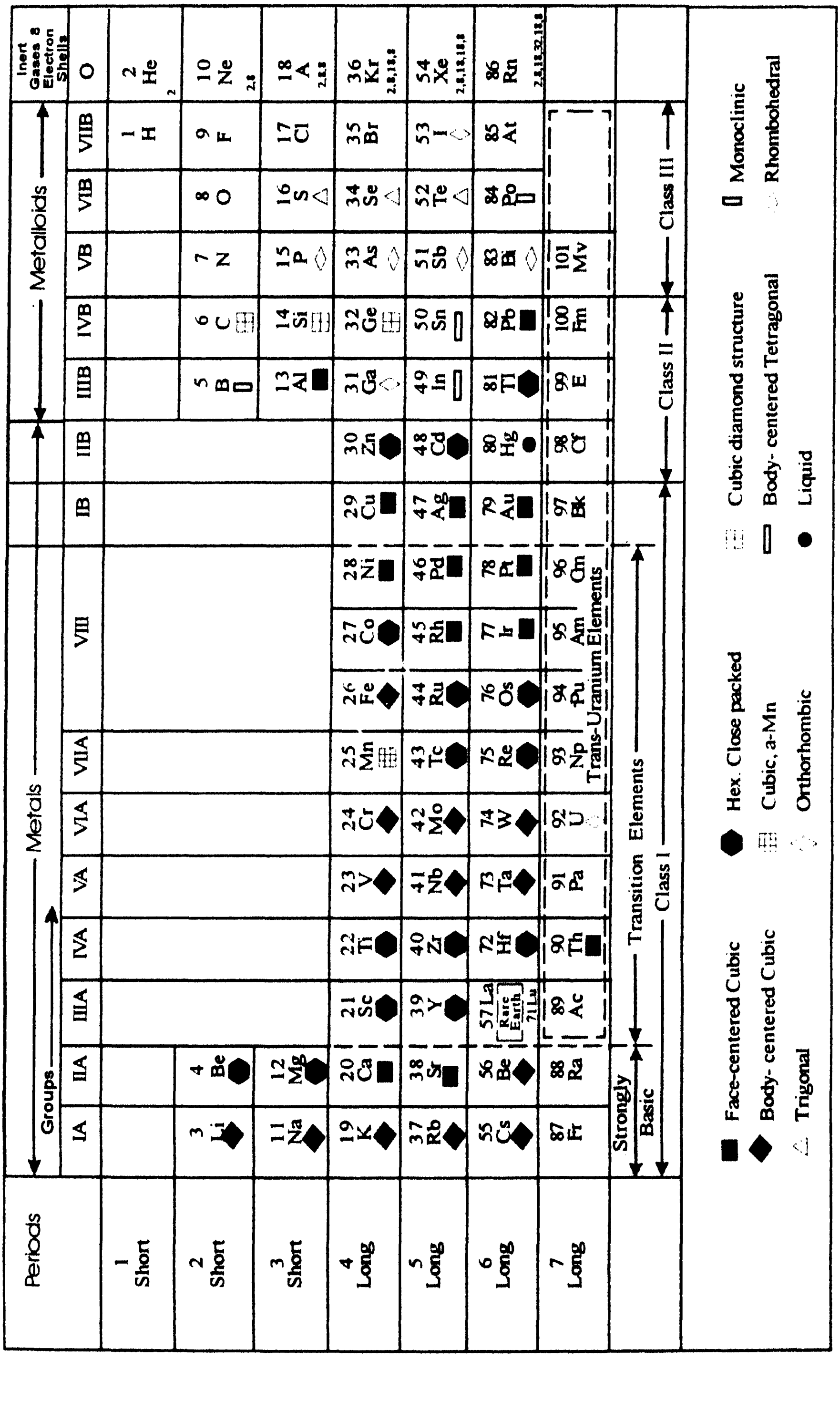

Fig. 1: The periodic classification of elements

gold, silver, copper, iron, lead, tin, mercury and zinc! A metal like aluminium, so widely used today, could be produced first only in 1827! (Incidentally, the latest textbooks in physics and chemistry deal with up to 108 chemical elements which include *all* the 92 naturally occurring ones plus 16 more that have been *artificially* produced in nuclear reactors and accelerators.)

Apart from being among the earliest of metals known and used by man, the metal iron has steadily grown in stature, particularly in the last two centuries, to become—technologically and commercially—the most important metal of today. The global *annual* output of metals has been around 800 million tonnes in recent years. The amazing fact is that iron in the usable forms of cast irons and steels (which are merely iron-base or ferrous alloys, containing besides iron small percentages of some other elements, principally carbon) accounts for *more than 95 per cent* of this output. *Modern* India is yet to assert itself as an important producer of this commercially crucial metal, but *ancient* and *medieval* India did its countrymen proud and made a tremendous impact on the world scene through many a spectacular achievement in iron and steel technology. In fact, according to present-day discerning scientists and technologists, India's most significant contribution to ancient metallurgy has been in the field of iron and steel.

Very little was known or studied of ancient Indian history till the beginning of the nineteenth century. Actually, it was in 1861, a few years after India's first war for independence (1857), that systematic archaelogical explorations commenced in North India at the initiative of Colonel A. Cunningham, the then English Chief Engineer of the North-Western Provinces and later Major-General, Royal Engineer (Bengal). Soon enough the archaeological discoveries brought home to Indians the past glory and greatness of their culture. The Indian subcontinent's earliest and best-known prehistoric civilizations and cultures as unearthed by large-scale excavations, have been grouped under the broad heads 'Indus Valley Civilization' and 'Harappan Culture' respectively. They are today associated with the sites of Mohenjo-Daro, Harappa, Taxila, Kalibangan and Lothal, of which the former three are found in Pakistan of today and the latter two in Rajasthan

and Gujarat, respectively, in India. Flourishing from about 2800 B.C. for a millennium and dying a rather sudden and mysterious death around 1700 B.C., possibly due to either a natural calamity or foreign invasion, the Indus Valley inhabitants displayed considerable talent in creating pottery and ceramics and more than a passing acquaintance with metals such as gold, silver, copper, lead and tin. However, the Harappans were *not* familiar with iron, i.e., they had not developed the high temperature technology needed for smelting iron ores, despite achieving proficiency in many other arts and technologies.

The Presence of Iron on Indian Soil

According to evidence presently available, which is, however, not universally accepted and, in fact, considered as conservative by many a scientist, the Iron Age was ushered into India around 1000 B.C., during the Vedic period, centuries after the metal iron had made its appearance in the West. The earliest reference related to the use of iron in India is due to Herodotus, the Greek historian, in reference to the battle (around 480 B.C.) at Thermopylae. In this battle, Indians were part of the Persian army and had used cane arrows fitted with iron tips. Later, we have on record a report concerning King Porus's gift of 100 talents (about 30 lb) of steel to Alexander the Great after the historic battle of 326 B.C. In the *Rig* and *Yajur Vedās*, the metal iron is referred to first as Ayas and later as *Kṛṣṇāyas* (black metal) or *Śyāmayās* (dark metal) to distinguish it from *Lohitāyas* (red metal) or copper. These references confirm that by 500 - 400 B.C. a high degree of perfection in making steel had been attained by Indians, even though the technological details regarding extraction of the metal from the ores are not available. The celebrated authority on medical science, Suśruta (third or fourth century B.C.), has described in his book dozens of surgical instruments, made of steel. Apart from the *Atharva Veda* and some *Upanishads*, the two great Sanskrit epics, *Rāmāyana* and *Mahābhārata*, provide ample evidence for the multifarious uses of iron. Many of our *Purānas* also abound in vivid descriptions of swords, spears, maces, shields, shoes of war horses, tyres of chariots and other martial paraphernalia made of iron. The innumerable stone edicts of Ashoka, the great

Mauryan emperor, whose reign began in 269 B.C., also bear witness to the extensive deployment of sharp iron chisels and hard steel tools for rock cutting.

Western scholars and scientists were greatly impressed with the facts unearthed by archaeologists, historians and technologists, both Indian and foreign, concerning the peaks recorded by ancient and medieval Indian metallurgy. The English scientists did not hesitate to use superlatives to describe the ingenuity of Indian craftsmen, as has been brought out by Indian metallurgists K. N. P. Rao, C. V. Sundaram and N. R. Srinivasan in their recent informative articles on the Indian iron and steel industry:

> The antiquity of the Indian process for making steel is no less astonishing than its ingenuity. We can hardly doubt that the tools with which the Egyptians covered their obelisks and temples of porphyry and syenite with hieroglyphics were made of Indian steel. There is no evidence to show that any of the nations of antiquity besides the Indians were acquainted with the art of making steel. The references which occur in Greek and Latin writers on this subject serve only to add to their ignorance of it; they were acquainted with the qualities and were familiar with the use of steel, but they appear to have been altogether ignorant of the mode by which it was prepared from iron .... The claims of India to a discovery which has exercised more influence upon the arts conducing to civilisation and the manufacturing industry than any other within the whole range of human invention are altogether unquestioned.
>
> *T.A. Heath* (1839)

> It is not many years since the production of such a pillar as the one near Delhi would have been an impossibility in the largest foundries of the world, and even now there are comparatively few places, where a similar mass of metal could be turned out.
>
> *V. Ball* (1881)

> Without doubt, therefore, the process of making iron and steel, has been used in India for thousands of years .... It may, therefore, easily have been the case that the ancient Egyptians were familiar with Indian iron and steel and either imported the material or obtained the services of Indian workers in metals to produce the necessary material for the tools employed on their great stone monuments.
>
> *Sir Robert Hadfield* (1912)

Wootz : India's Famous Crucible Steel

Among India's great metallurgical achievements of the ancient and medieval ages, the celebrated Iron Pillar at Delhi occupies a pre-eminent position in the field of *iron technology* and will be dealt with exhaustively in the remaining Chapters. It is, however, appropriate to refer here to what is considered by many discerning metallurgists as ancient and medieval India's foremost contribution to *steel technology*, viz., the innovation and production of an ultra high-carbon steel, that has come to be known as *Wootz* the world over, which is also referred as *khus* in some parts of India. The former is generally accepted as a corrupt form of *wookku*, the word for steel in Kannada and Telugu. There has also been a suggestion that the word comes from the Telangana region of Andhra Pradesh and refers to the carbonization of wrought iron in a crucible.

The notion that has lingered for a long time in certain quarters that iron and steel technology was brought to India *from* West Asian countries such as Persia and Turkey has now been subject to serious question. Archaeological evidence based on radio-carbon dating has clearly shown that iron was being made, albeit in small quantities, all over India from Kanyakumari to Kashmir, including Pakistan, during the first millennium B.C. There is, however, no continuous link, and it is quite possible that the industry developed sporadically and independently at several regions, since good iron ore was available in most parts of the country. Due to the absence of recorded communication, the 'know-how', in this area as in the fields of religious rituals and fine arts, got shrouded in mystery and was handed down orally and selectively from one person to another within small groups.

There is, however, very strong and reliable evidence that after the second century A.D. trading was carried out in Indian steel and this became a well-recognized commodity for the making of swords and armour in Persia, the Middle-East and Arab countries. Many references in literature and scientific works of the Islamic period make it clear that crucible steel making was an Indian invention, but this information was kept in the dark for some time.

It was divulged only during the eighth and ninth centuries A.D. to the rest of the world by Islamic writers and traders. Indian steel became almost synonymous with Damascus swords and was exported to the Far East as well—to Sumatra, Borneo and China. By A.D. 1500 Indian steel had become an important and coveted commodity in Asian and international trade.

In modern parlance 'Wootz' may be described as a high-carbon steel made by the crucible process with the carbon content varying from 0.5 to 2.1 per cent by weight. Such steel was made in two grades: (i) 'Soft' grades with 0.5 to 0.8 per cent carbon and (ii) 'hard' grades with 1.1 to 2.1 per cent carbon. A typical carbon content in 'Wootz' for lethal weapons could be about 1.5 per cent carbon. Apart from the physical properties, the characteristic or distinguishing feature of the Damascus swords made from such 'Wootz' has been the water surface markings known as 'waterings'.

'Wootz' has aroused, surprisingly, a deep interest in recent years in the USA, the UK and some other European countries, particularly Germany. Such interest has been mainly due to the unique properties of super-plasticity and high-impact hardness associated with these steels. As a matter of fact, scientific studies of 'Wootz' began as early as in seventeenth century. However, the initial experiments were directed toward rediscovering and re-creating Damascus swords with the 'waterings' or surface markings as in the original. Although the science underlying the unique properties of 'Wootz' is now understood reasonably well, it appears that further details of the traditional or 'primitive' technology may be necessary to reproduce *all* the physical and mechanical properties associated with this fabulous material.

Iron and Steel in Modern India

From the foregoing discussion, it is clear that the early Indian civilizations, at their peak were artistic, intellectual and innovative to a high degree. Their record of achievements in a variety of fields, particularly the metallurgy of iron and steel, is truly amazing — something that all Indians can be proud of even at this point of time.

But then a stage came, towards the end of the medieval period, when there set in a steady decline in strength, will and perseverance and India as a nation failed to withstand the external onslaughts and retreated rather pathetically into a defensive and static shell. With regard to indigenous developments, the period 1750-1950 should be considered as particularly tragic. This was the vibrant period of the Industrial Revolution in Europe, as also the golden period of the basic sciences in the West. Nothing of any consequence in science and technology happened in India during these two centuries, with the result that when India shook off the colonial yoke and became free in 1947, this great country had to suffer the humiliation of being grouped among under-developed countries!

There were, however, a few silver linings in the cloud. Starting with the establishment of the Barakar Works in 1875 (through Indo-British initiatives) at Kulti to make pig iron by modern methods, an important step forward was taken by the great Indian industrialist J.N. Tata through the launching of the Tata Iron and Steel Company at Sakchi (now Jamshedpur) in Bihar in 1907. Another far-sighted Indian, M. Visvesvarayya, a Civil Engineer and Dewan of Mysore, established the Mysore Iron and Steel Works at Bhadravati in 1919. All these developments constituted but a beginning for the mighty ventures that the country embarked upon in the field of iron and steel with the First Five-Year Plan in 1951 under the leadership of Independent India's first Prime Minister, Pandit Jawaharlal Nehru.

During the last seven Five-Year Plan periods, India has been able to develop a reasonably large base for making iron and steel through its new integrated steel works at Bhilai, Rourkela, Durgapur, Bokaro and Visakhapatnam. The overall progress in steel production has not been as satisfactory as one would have wished for, because of far too many constraints that these giant industries have had to face almost since their establishment. All the same, starting with the annual production of about one million tonnes of steel around 1948, India could produce around 12 million tonnes 40 years later. An annual output of over 20 million tonnes is envisaged for A.D. 2000 when the demand is expected to be about 25 million tonnes. These

figures have, however, to be compared with those of a country such as Japan to appraise India's overall performance in the global context. Japan produced *less than* one million tonnes of steel in 1948, but could produce a phenomenal *more than* 100 million tonnes well before 1988! And Japan achieved all this with *imported* iron ore!! As for world production, it had exceeded 700 million tonnes of steel per annum by this time !!!

There are some disquieting facts that have to be faced squarely. The per-capita consumption of steel is an indicator of economic and industrial advancement of a nation. As is well-known, India's per-capita figure in this regard is far below the world average (Table 1a). Modernization of technology and replacement of obsolete equipment are a 'must' for our steel plants, but the progress in this regard has been very slow for several reasons. Our average consumption of material and energy per ton of steel is perhaps *the highest* in the world, while our productivity index for iron is *the lowest*! Starting of new plants involves considerable capital expenditure (Table 1b), now rated at more than Rs. 25,000 per tonne and thus involving over Rs. 2500 crores for a million-tonne plant! It is clear that many hurdles have to be overcome for India to come on par with the developed countries.

It is necessary to recall today the pregnant and prophetic words spoken by a distinguished captain of India's steel industry, S.K. Nanavati of the Tata Iron and Steel Works, at an international symposium held in 1963 at Jamshedpur:

> An Indian can always be proud of the glorious past of his forefathers. Unfortunately the promise and the richness of experience in the ancient past have not been realised in later years. Today in free India, the young metallurgist should look backwards for inspiration to this bygone age when great things were accomplished and cherish the hope that he would be in a position in the not too distant future to emulate those who wrought the Iron Pillar at Delhi, and make his contribution to the advancement amd practice of the science and art of metallurgy.

Table 1 : Some relevant data on steel production for the year 1991.

(a) Production in selected countries

S.No.	Country	Per-capita steel consumption (in kg)	Production (in million tonnes)
1.	India	19.2	14.7
2.	China	68.3	67.2
3.	Brazil	88.5	20.6
4.	USA	439.2	88.7
5.	Germany	558.7	38.4
6.	Japan	607.7	110.3
	World average	150	

(b) Investment on projects at present levels

S.No.	Project	Approximate investment (Rupees/tonne)	Economic capacity (in million tonnes per annum)
1.	Integrated steel plant	27,500	3.00
2.	Ore pelletisation plant	2,500	2.00
3.	Sponge iron plant	6,000	1.50
4.	Hot rolling mill	18,000	1.00
5.	Cold rolling mill	9,000	0.20
6.	Galvanizing unit	6,500	0.05

* * *

Chapter I

FACTS AND FIGURES

It is now generally accepted by scholars and scientists alike that the famous Iron Pillar located at Mehrauli village on the outskirts of Delhi and not far from Qutab Minar (or Kutab Minar), another well-known monument and a tourist attraction, has been in existence for over 1500 years and that it was fabricated during the Gupta period (A.D. 320 to A.D. 495), when Indian civilization reached one of its zeniths and recorded some extraordinary literary, artistic and technological achievements. Known as "*Lohe-kī-Lāt*" i.e., Iron Pillar, in the local language and connected with numerous legends, this metallurgical marvel does not seem to have attracted the serious attention of researchers in the fields of either history and archaeology or science and technology till the second quarter of the nineteenth century. One need not be surprised by this rather incredible fact because the age of modern science and scholarship began only in the eighteenth century and had its first blossoming in Europe, even as India languished in a shocking state of disarray, apathy and stupor during this period.

India's great poet and Nobel Laureate, Gurudev Rabindranath Tagore, surveys the trials and tribulations of our country in that period in his well-known poem *Jana Gana Mana* written in the earlier part of the twentieth century. The first stanza of this moving poem has deservedly become India's national anthem, but most seem unaware that there are four more stanzas in this beautiful poem and that, in fact, this poem in its entirety has been recited by the poet and been recorded in his own voice. In the fourth stanza, Gurudev describes the India of the nineteenth century most aptly: "*Ghora - Timira - Ghana - Nibida-Niśithe-Pīdita - Mūrcchita - Deśe...*" (A country enveloped

in dense and deep darkness, as at the deadly midnight hour, afflicted by many ills and in a state of stupor...)

No wonder, little attention was paid then in this country to the unusual features of what is recognized today as technologically the most significant among the historical remains in and around India's capital.

The first reports on the Iron Pillar emanate, not surprisingly, from British soldiers and travellers who were already moving around in the Indian subcontinent in gradually increasing numbers during early 19th century. As recorded by Carr Stephen and J. F. Fleet in 1876 and 1888 respectively, one Captain Archer, who accompanied Lord Combermere in 1828 on his tour of North-West India, reported on the Delhi Pillar, describing the inscription on it as "of unknown antiquity" and which "nobody can read." In 1831 Lieutenant William Elliot of the 27th Regiment N.I. made a facsimile of this inscription at the request of Dr. Mill of Bishop's College, but the work was "so ingeniously mismanaged that not a single word could be made out!" A few years later Captain T.S. Burt of the Engineers made a reliable ink impression of the inscription and passed it on to James Prinsep, one of the greatest of Indian antiquaries of the nineteenth century. This provided the impetus for the first important paper on the Delhi Pillar. It was authored by Prinsep and published in 1838 in the *Journal of the Asiatic Society of Bengal* with a lithograph of the inscription, his reading of its Sanskrit text in ancient *Nāgari* script, a modern *Nāgari* transliteration of the same and his own English translation.

Following Prinsep's pioneering efforts, General A. (later Sir Alexander) Cunningham (1871) and Dr. Bhau Daji (1875) of Bombay threw more light on the six-line Sanskrit inscription on the Pillar. The former thought that the inscription belonged to the third or fourth century A.D., while the latter opined that it should be assigned a somewhat later date. Daji presented a paper on this subject on April 13, 1871 at Bombay to the members of the Asiatic Society and the same was published in 1875 in the Society's journal. Daji's important paper contained a revised

version of the text of the poetic inscription and its translation, including the correct reading of the king's name as Chandra with an improved lithograph reduced from a copy on cloth made by one Dr. Bhagwan Lal Indraji. In his famous *Reports*, published in 1871 but covering the years 1862 to 1865, Cunningham has drawn attention to other inscriptions on the Pillar, mentioning, quite correctly, that "they are more numerous than important."

Stephen recorded in 1876 that "we have no trust-worthy account of the original location of this Pillar or its age, but tradition, silent as to its maker, attributes its erection to Anaṅg Pāl I (also written as Anaṅga Pālā) and places it in the temple of Rāi Pithora". When the temple was converted to a mosque by Qutb-ud-din Iback (around A.D.1190), the Pillar was permitted to stand where it was, but neither tradition nor history discloses the name of its maker or his purpose in making it. Daji was of the view that in the mosque and buildings around, there are stones which originally belonged to Jain, Saiva and Vaishnava temples of the tenth or eleventh century A.D.

As Stephen has further noted, the inscription by Anaṅg Pāl II about the erection of the Pillar is brief and has the date 1109 *Samvat,* i.e., A.D. 1052, obviously for the new location. There is also a modern *Nāgari* inscription of six lines dated 1767 Samvat (A.D. 1710). There are two records of Chohan Raja Chatra Sinha, both dated 1883 Samvat (A.D. 1826). The writings on the Pillar are completed by two Persian inscriptions dated A.D. 1651 and 1652 recording just names, of perhaps visitors to the mosque and the Pillar.

Descriptions of the Pillar

As noted by W.E. Bardgett and R.F. Stanners in the February 1963 special issue on the Iron Pillar of the *National Metallurgical Laboratory (NML) Technical Journal*, the Delhi pillar has, for a long time, provoked the admiration of antiquarians and the curiosity of metallurgists, principally for its large size and its excellent state of preservation. Travellers' tales from mid-nineteenth century reporting on its appearance are scattered through

scientific and archaeological literature, but are of interest only for their flights of fancy. Some have described it as several times its actual size—at least 60 feet high, according to one report—while others have claimed it to have been a single piece of casting, even though the marks of joining are clearly visible, "presumably where balls of iron in a plastic state were hammer-forged together."

Stephen has described the Pillar, quite unerringly even in 1876, as "a solid shaft of wrought iron" although most travellers around that period described its material as "mixed metal", "brass", "bronze", "soft iron" and "cast iron". Even Daji was emphatic around this time about his statement that "iron forms no portion of this monument, and it is a compound (alloy) of several metals". However, Stephen had the knowledge that one Dr. Murray Thompson had analysed a small bit of the Pillar for General Cunningham and thus was quite certain that the metal was "pure malleable iron with 7.66 specific gravity."

Both Stephen (1876) and V.A. Smith (1897) agree on the location and dimensions of the Pillar in their writings. Smith's detailed description in this regard deserves reproduction in full and may be considered along with Plates 1 and 2:

> The great mosque built by Qutb-ud-din Ibak in A.D. 1191 and subsequently enlarged by his successors, as well as its minaret, the celebrated Qutab Minar, stands on the site of Hindu temples, and within the limits of the fortifications known as the Fort of Rāi Pithaura, which were erected in the middle or latter part of the twelfth century to protect the Hindu city of Delhi from the attacks of the Mussalmans, who finally captured it in A.D. 1191. These buildings are situated about nine miles south of modern Delhi, or Shāhjahānābād, and lie partly within the lands attached to the village of Mihirauli (Mehrauli, as it is known today), an evident corruption for *Mihirapuri.*
>
> The Iron Pillar stands in the courtyard of the mosque at a distance of about ten yards outside its great arches. The total length of the Pillar from the top of the capital to the bottom of the base is 23 feet 8 inches. Twenty-two feet are above ground, and only 1 foot 8

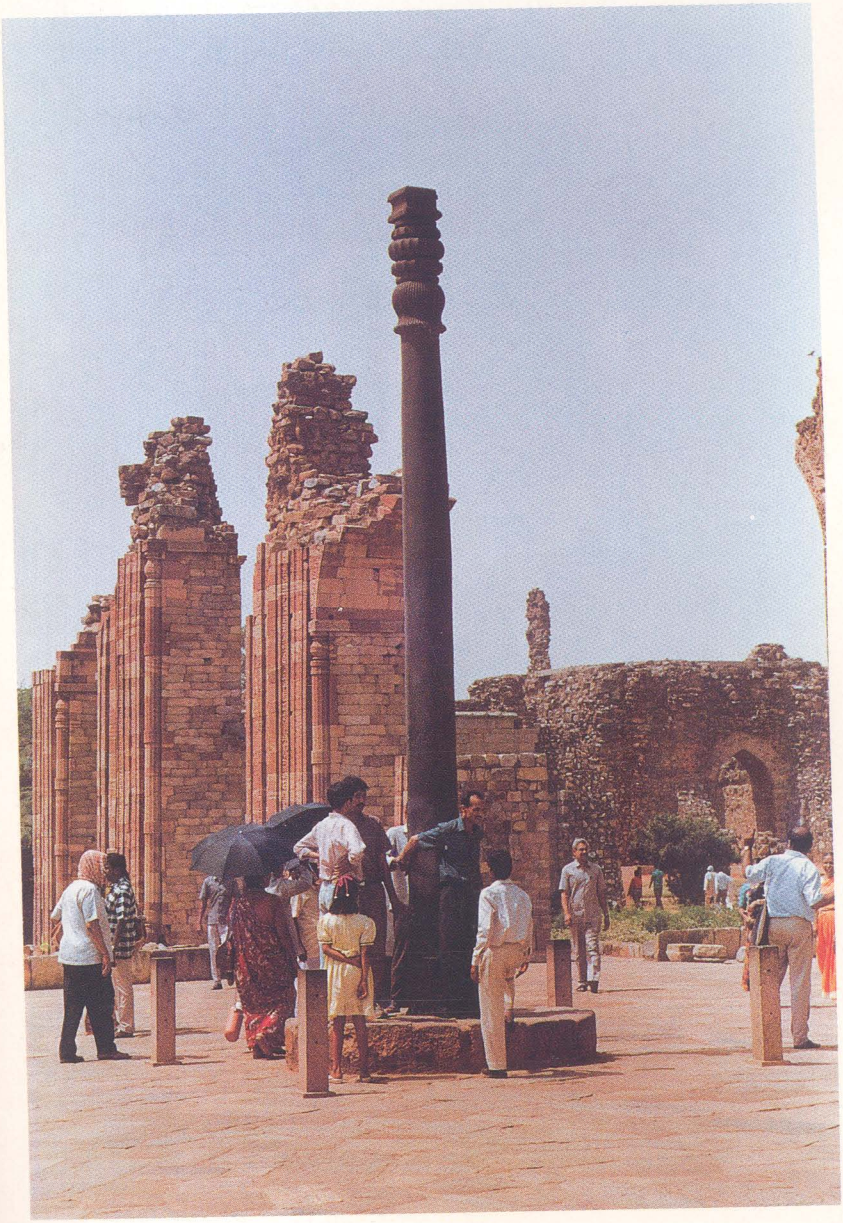

Plate 1: The Pillar with temple ruins around

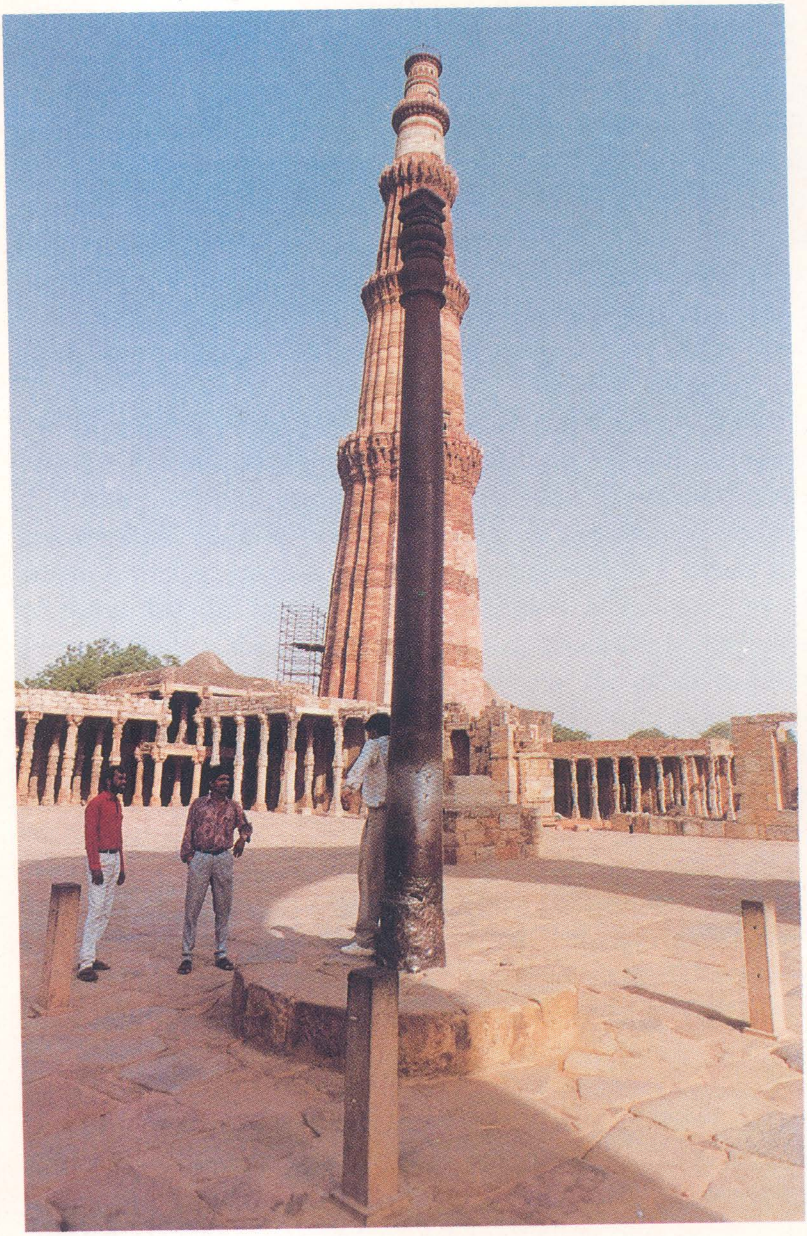

Plate 2: View of the Pillar along with Qutab Minar

Recent Data on the Pillar

Scientific studies on the Pillar may be considered to have made a beginning with the classical paper of the distinguished metallurgist Sir Robert Hadfield in the *Journal of the British Iron and Steel Institute* in 1912. During the last 80 years, both Western and Indian scientists have undertaken a number of investigations to probe the nature (composition, structure., etc.,) of this fascinating monument, often referred to as a "metallurgical enigma". In our country, apart from the Archaelogical Survey of India, two Laboratories of the Council of Scientific and Industrial Research (CSIR), viz., the National Metallurgical Laboratory, Jamshedpur, and the National Physical Laboratory, New Delhi, have made significant contributions in this area.

The dimensions of the Pillar, as recorded by one Ms Cummings for Sir Hadfield in 1912 are as follows:

Total length	23' 8"	(7.21 m)
Portion above ground level	22'	(6.71 m)
Portion below ground level	1' 8"	(50.8 cm)
Upper diameter (below the decoration)	12.5"	(31.8 cm)
Lower diameter	16.5"	(41.9 cm)

Panchanan Neogi made the following measurements in 1914 :

Total length	23' 8"	(7.21 m)
Diameter at the base	16.4"	(41.7 cm)
Diameter at the top capital	12.05"	(30.6 cm)
Engraved capital	3' 6 "	(1.07 cm)

It was believed that a few inches below the surface, the Pillar expands into a bulbous form to a diameter of 2 ft. 4 in. (71.12 cm) and rests on a grid of iron bars, which are fastened with metallic lead into the stone pavement.

In 1961, on the eve of the centenary of the Archaeological Survey of India, the Pillar was dug out for chemical treatment and preservation, and then re-installed by embedding the

underground part in a newly constructed masonry pedestal. Following the excavation a detailed examination of the entire Pillar (exposed portion, buried portion and the capital at the top) was carried out by Dr. B.B. Lal, chief archaelogical chemist, and measurements of different parts of the Pillar were taken in detail. The state of the Pillar in general and the condition of the corroded and rusted areas in particular were photographically documented. The measurements then recorded by the Arachaeological Survey of India are as under:

Total length of the Pillar	23 ft. 6 in.	(7.16 m)
Portion below ground up to the height of the raised pedestal	3 ft. 1 in.	(94.0 cm)
Cylindrical portion of the Pillar exposed to view	17 ft.	(5.18 m)
Height of the capital with decoration	3 ft. 5 in.	(1.04 m)
Diameter at the base of the pedestal	1 ft. 4.7 in.	(42.4 cm)
Diameter at the top below the capital	11.85 in.	(30.1 cm)
Diameter at the base (underground)	2 ft. 0.59 in.	(62.5 cm)
Topmost square, flat surface of the capital	1 ft. x 1 ft. (30.5 cm x 30.5 cm)	
Diameter of the iron cylinder fitted at the top	8 in.	(20.3 cm)
Length of the slot or groove for the flagstaff	6 in.	(15.2 cm)
Depth of the slot or groove for the flagstaff	1 ft. 3 in.	(38.1 cm)

The capital of the Pillar is made up of a solid cylinder of iron fitted into a deep groove at the top end. The upper end of the cylinder has a flat square base with a rectangular slot about 15.2 cm long at the centre, evidently provided for holding a

flagstaff. Since the slot, about 38 cm deep, is exposed to the atmosphere, a lot of rain water accumulates in it along with rain-washed and wind-blown dust. The original weight of the Pillar was over 6 tonnes.

The latest, and perhaps the most exhaustive, measurements of the Pillar were made in 1989 by Bindal *et al.* of the National Physical Laboratory, New Delhi, while subjecting it to ultrasonic non-destructive testing studies. Fig. 2 gives its dimensions comprehensively, while Fig.3 and Table 2 bring out the variations in its diameter with height.

Table 2 : Diameter of the Iron Pillar at various heights above the platform level

Height (m)	**Diameter at position in Fig. 2 (in cm)**			
	1	2	3	4
0.25	43.37	—	Rough surface	—
0.50	43.24	42.54	41.46	41.27
0.75	41.23	41.46	41.46	41.52
1.00	40.19	40.95	40.95	40.89
1.25	39.68	40.32	40.19	40.06
1.50	38.67	39.30	39.24	39.17
1.75	37.52	38.48	38.73	38.67
2.00	37.46	38.16	38.16	37.84
2.25	37.59	37.17	37.59	37.59
2.50	37.46	37.46	37.27	37.33
2.75	37.02	37.14	37.08	36.89
3.00	36.38	36.70	36.70	36.51
3.25	36.83	36.57	36.70	36.89
3.50	36.83	37.02	36.76	36.89
3.75	36.06	36.57	36.06	36.06
4.00	35.17	35.56	35.56	34.86
4.25	34.03	34.67	34.29	34.22
4.50	33.52	33.90	33.52	32.76
4.75	32.06	32.51	31.11	31.24
5.00	29.17	30.98	30.73	29.17

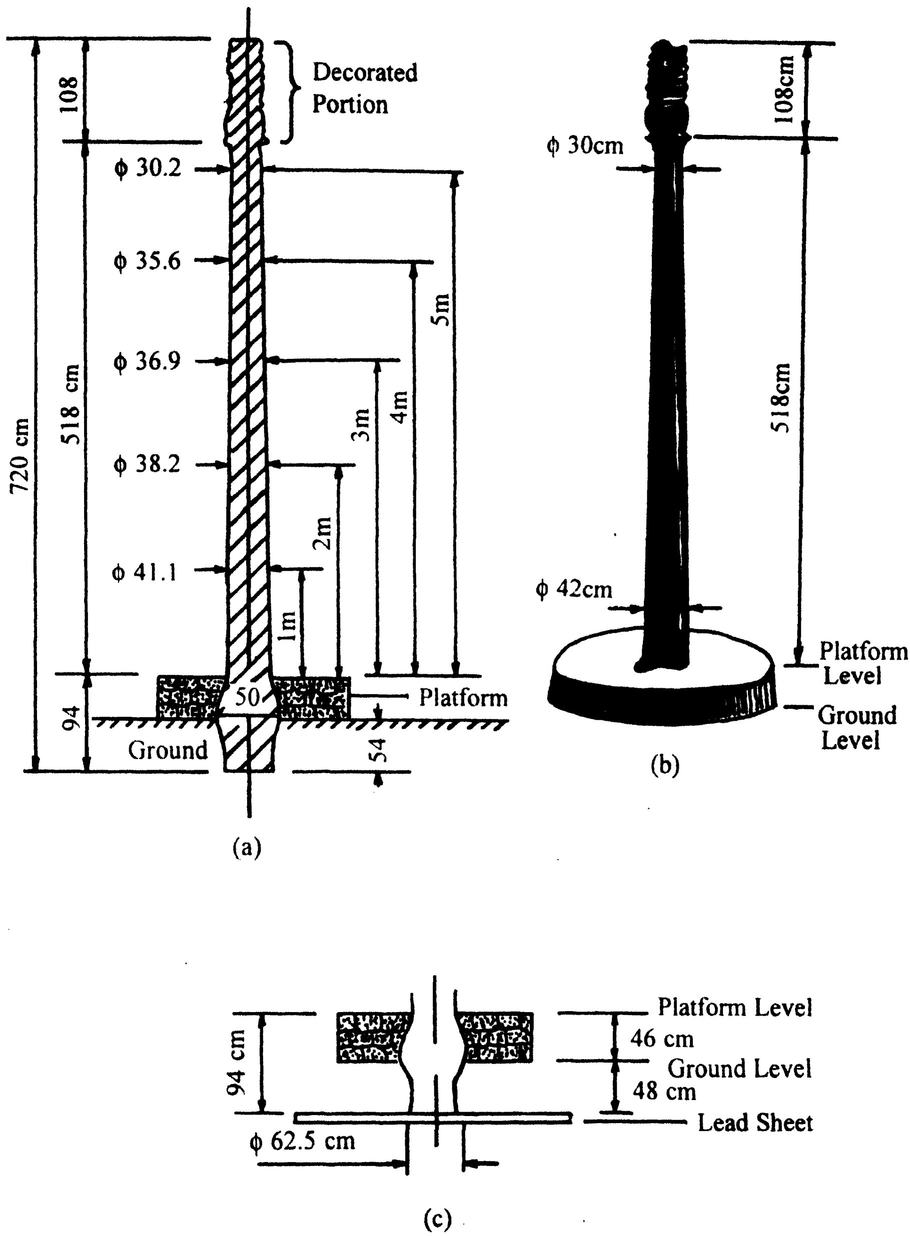

Fig. 2: The Iron Pillar and its physical dimensions:
a) Sketch of the Pillar; b) Visible portion; c) Portion hidden below the platform level (*Courtesy*: Bindal *et al*, National Physical Laboratory, New Delhi, 1989)

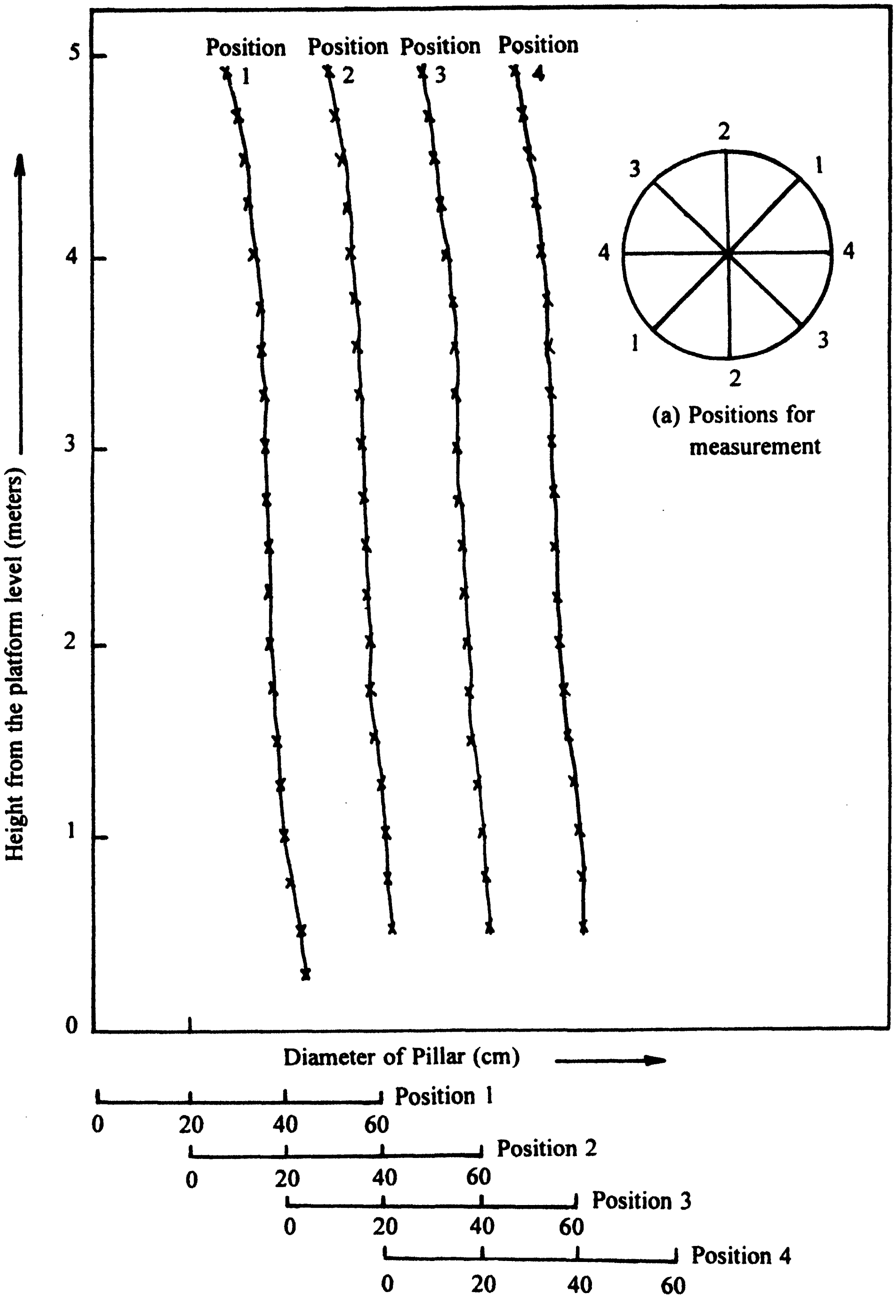

Fig. 3: Variation of diameter of the Iron Pillar with height
(*Courtesy*: Bindal *et al*, National Physical Laboratory, New Delhi, 1989)

The chemical analysis of small samples taken from the Iron Pillar has been carried out several times, starting from the earliest one reported by Hadfield in 1912. The Chief Archaeological Chemist (Dr. B.B. Lal) associated with the Archaeological Survey of India, carried out analysis in 1945 at the Laboratories of the Chief Metallurgical Inspector, Government of India, Jamshedpur, and found that his values were quite close to those reported by Hadfield some 30 years earlier. Around 1963, thanks to the initiative of Dr. B.R. Nijhawan, Director, National Metallurgical Laboratory, Jamshedpur, chemical, spectro-chemical and electron-probe analyses were undertaken on a piece weighing about 4 gm taken from another portion of the Pillar. Although there were variations in the percentage of carbon, silicon and phosphorus, as brought out by Table 3, it was clear that the iron of the Pillar is astonishingly pure i.e., low in carbon in particular, *vis-á-vis* the commercial iron varieties of today.

Table 3: Chemical analysis of samples taken from the lower portion of the Iron Pillar (in weight per cent)

Element	**Hadfield** (1912)	**Lal** (1945)	**Ghosh** (1963)	**Lahiri** (1963)
Carbon (C)	0.08	0.09	0.23	0.28
Silicon (Si)	0.046	0.048	0.026	0.056
Phosphorus (P)	0.114	0.174	0.180	0.155
Manganese (Mn)	Nil	Nil	Nil	Nil
Sulphur (S)	0.006	0.007	trace	0.003
Nitrogen (N)	0.032	——	0.007	——
Copper (Cu)	0.034	——	——	——
Total Iron (Fe)	99.72	99.67	99.77	——
Specific gravity	7.81	——	7.67	7.50

The Inevitable Legends

Facts and figures alone count for a rigorous scientific study of the Pillar, but the legends associated with it are interesting and worth recording on that account. It is also relevant to note here that the natives knew the Pillar traditionally as *Lohe-kī-Lāt* (Iron Pillar), and that is what it turned out to be on scientific investigation, despite many doubts in this regard for the best part of nineteenth century.

According to universal tradition, as Cunningham has it, the Iron Pillar was erected at its present location by Bilan Deo, or Anaṅg Pāl, the founder of the Tomar dynasty, who was assured by a learned Brahman that, as the foot of the Pillar had been driven so deep into the ground that it rested on the head of Vāsuki, the legendary king of serpents, who supports the earth, and hence was immoveable, and that the dominion would remain in his family as long as the Pillar stood. But the Rāja, doubting the truth of the Brahman's statement, ordered the Pillar to be dug up. When this was done, the foot of the Pillar was found wet with the blood of the serpent king, whose head it had pierced. Regretting his unbelief, he raised the Iron Pillar again; but, owing to the king's former incredulity, every plan to fix the Pillar firmly now failed and, in spite of all his efforts, it still remained loose *(dhīla)* in the ground. And this i.e., Dhili Killi (Loose Pillar), is said to have been the origin of the name of the ancient city of *Dhīli* (now Delhi). In fact, the most recent excavations at Lal Kot near the site of the Iron Pillar have unearthed what is widely believed to be the structural remains of the first city of Delhi built by Anaṅga Pāla II of the Tomar dynasty in mid-eleventh century A.D. The Archaeological Survey of India, which started this excavation work in February 1992 has claimed this finding as a significant breakthrough.

This tradition has been variously reported by different authorities, but the main points are the same in all. One Colonel Tod states that the Iron Pillar is said to be resting on the head of the *Śes Nāg*, who is the same as *Vāsuki*, the serpent king. A lady traveller, who visited Delhi between 1804 and 1814, heard of the tradition in a somewhat different way. A Brahman told the king

that if he could place the seat of his government on the head of the snake that supports the world, his kingdom would last for ever. The Iron Pillar was accordingly driven into the ground on its present site, under the superintendence of the Brahman, who announced that the lucky spot had been found. On hearing this, a courtier, jealous of the Brahman's influence, declared that the Pillar was not placed over the serpent's head, but that he could point out the true place, which he had seen in a dream. The Pillar was accordingly taken out upon the Raja's orders, and, conforming to the Brahman's prediction, the foot of the pillar was found wet with the blood of the serpent's head.

The foregoing tradition is also imperfectly related in Purchase's *Pilgrims*, on the authority of English travellers who visited India during the reigns of the great Moghul kings Jahāngīr and Shāhjahan. Purchase states that the Rāse (Rāja) who founded Delhi, "by advice of his magicians, tried the ground by driving an iron stake, which came up bloody, having wounded a snake. This the Ponde (Pande or Pandit), or magician, said was a fortunate sign. In all these different versions of the erection of the Iron Pillar, the main points of the story are the same, and the popular belief in this tradition is confirmed by the well-known verse :

Killi to dhili bhai,
Tomar bhaya mat hin.

The Pillar has become loose,
The Tomar's wish will not be fulfilled.

What was the origin of this tradition, and at what time it first obtained currency, may never, perhaps, be known. However, we are justified in hazarding a guess that the long reign of the Tomar dynasty must have first led to an opinion of its durability which would then have been naturally compared with the evident stability with which the Iron Pillar was fixed in the ground. We have an exact parallel case in the well-known saying about Rome and the Coliseum, which the verse of Byron has rendered famous:

While stands the Coliseum, Rome shall stand,
When falls the Coliseum, Rome shall fall.

* * *

Chapter II

THE INSCRIPTIONS

There are many inscriptions on the Iron Pillar at Delhi, but, by far, the most significant (and the earliest) of them is the six-line Sanskrit inscription in archaic *Gupta Brahmi* script on its upper portion. Although this inscription could be deciphered and translated in the very first and seminal work on the Pillar by James Prinsep in 1838, many aspects of it are still shrouded in mystery and dogged by controversy. The inscription is not dated, but refers to the conquests of a powerful king named Chandra. As the dynastic particulars of this great ruler are not recorded in the inscription, there has been no unanimity amongst scholars about the exact identity and precise historical context in terms of this king's specific period or rule. On the grounds of palaeography, content, language, style of execution and so on, the Pillar is considered by most scholars to belong to the early Gupta period, i.e., later fourth or early fifth century A.D. However, there are many uncertainties and imponderables which will be discussed at length in the next chapter.

It would be relevant to refer here to the equally significant, but less mysterious, inscription on the Allahabad stone pillar devoted entirely and unambiguously to a recital of the glory, pedigree and conquests of the early Gupta king, Samudra Gupta (see Table 4). The round monolith sandstone column on which this long 33-line *'praśasti'* (eulogy) has been engraved is 35 feet in height, dates from the third century B.C. (as shown by the famous edicts of Emperor Ashoka on it) and now stands in a conspicuous position inside the Fort of Allahabad in Uttar Pradesh. Although the upper portions of this inscription have suffered considerable damage, the really important part of the inscription dealing with significant historical and genealogical facts (from lines 19 to 30) is fortunately in a state of excellent preservation

and is decipherable without the slightest doubt from beginning to end. This inscription is also in *Gupta Brāhmi* script and the writing resembles, in many respects, that on the Iron Pillar at Delhi. This similarity acquires considerable importance in the light of the ongoing controversy on whether Samudra Gupta or his son Chandra Gupta II is the king referred to in the inscription on the Delhi Iron Pillar.

Table 4 : Genealogy of the important Gupta kings

CHANDRA GUPTA I (Vikrama I or Vikramāditya I) Mahārājādhirāja Married to Kumāradevī of the Lichchhāvi family (A.D. 320 - 340) ॥ **SAMUDRA GUPTA** (Kācha) Mahārājādhirāja Married to Dattadevī (A.D. 340 - 376) ॥ **CHANDRA GUPTA II** (Vikrama II, Vikramāditya II or Vikramāṅka) Paramabhaṭṭāraka and Mahārājādhirāja Married to Dhruvadevī (A.D. 376 - 414) ॥ **KUMĀRA GUPTA I** (Mahendra or Mahendrāditya) Mahārājādhirāja Married to Anantadevī (A.D. 414 - 455) ॥ **SKANDA GUPTA** (Kramāditya) Paramabhaṭṭāraka and Mahārājādhirāja (A.D. 455 - 467)

The Inscription on King Chandra

As has been observed by practically all scholars who have examined the inscription on the Delhi Pillar, its writing is in an excellent condition throughout, owing to the nature of the substrate viz., rustless, smooth iron, on which it is engraved. The six lines of the inscription cover a space of about 2 feet 9.5 inches in breadth 10.5 inches high. The bottom line is about 7 feet 2 inches above the stone platform round the lower part of the column. The size of the letters varies from 0.3 to 0.5 inch and the engraving is on the whole very good (see Plate 5). However, the metal has closed up over some of the strokes and this has, in turn, led to a rather imperfect appearance of a few letters in the lithograph (see Fig. 4).

As early as in 1888 Fleet had noted that the characters on this inscription belonged to the northern class of alphabets and, allowing for the stiffness resulting from engraving on so hard a substance like iron of this column, they approximate, in many respects, rather closely the Allahabad posthumous pillar inscription on Samudra Gupta. As a distinguishing feature between the two, one has to take note of the very marked *mātrās* on horizontal top strokes of the letters, which seem to correspond to the Bilsad pillar inscription of Kumara Gupta in Eta district of Uttar Pradesh, which is generally assigned the date A.D. 415–416.

The text and translation, as given by Fleet over 100 years ago are as follows:

TEXT

1. *Yasy-odvarttayataḥ pratīpam-uraśa śattrūn-samety-āgatān-Vaṅgeshv- āhavvarttino-bhilikhita khaḍgena kīrttir-bhuje*

2. *Tīrtvā sapta mukhāni yena samare Sindhor-jjitā Vāhlikā yasyādyāpy—adhivāsyate jalanidhir-vvīryy-ānilair-ddakshiṇaḥ (II*)*

3. *Khinnasy-eva visṛjya gāṁ narapater-ggām-āśritasyetarāṁ mūrt (t*)yā karmma-jit-āvaniṁ gatavataḥ kīrt(t)yā sthitasya kshitau*

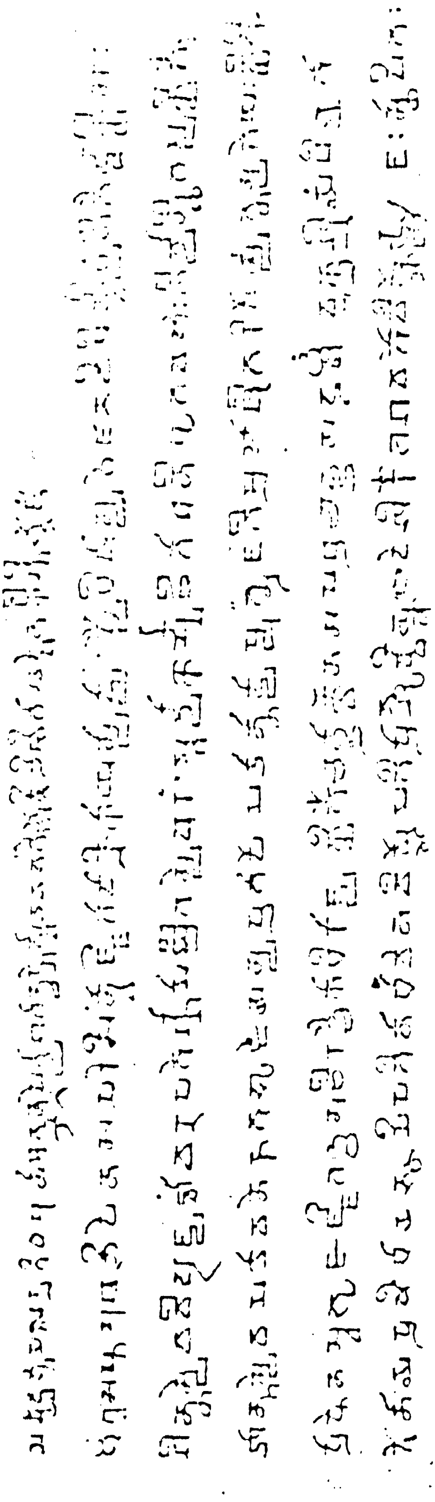

Fig. 4: The main inscription on the Iron Pillar, referred to as the Mehrauli Prasasti.

4. *Śāntasy-eva mahā-vane hutabhujo yasya pratāpo mahānn-ādyāpy-utsṛjati praṇāśita-ripor-yyatnasya śeshaḥ kshitim (11*)*

5. *Prāptena sva-bhuj-ārjjitañ-cha suchirañ-ch-aikādhir-ājyam kshitau Chandrāhvena samagra-chandra-sadṛśīm vaktraśriyaṁ bibhratā*

6. *Ten-āyaṁ praṇidhāya bhūmipatinā dhāvena Vishṇo (shanau) matiṁ prānśur-Vvishṇupade girau bhagavato Vishṇor-dhvajaḥ sthāpitaḥ (11*)*

TRANSLATION

(Lines 1 and 2) He, on whose arm fame was inscribed by the sword, when, in battle in the Vaṅga countries, he kneaded (and turned) back with (his) breast the enemies who, uniting together, came against (him); he, by whom, having crossed in warfare the seven mouths of the (river) Sindhu, the Vahlikas were conquered; he, by the breezes of whose prowess the southern ocean is perfumed even today.

(Lines 3 and 4) He, the remnant of the great zeal of whose energy, which utterly destroyed (his) enemies, like (the remnant of the great glowing heat) of a burned-out earth; though he, the king, as if wearied, has quit this earth, and has gone to the other world, moving in (bodily) form to the land (of paradise) won by (the merit of his) actions, (but) remaining on (this) earth by (the memory of his) fame.

(Lines 5 and 6) By him, the king, who attained sole supreme sovereignty in the world, acquired by his own arm and (enjoyed) for a very long time; (and) who, having the name of Chandra, carried a beauty of countenance like (the beauty of) the full moon, having in faith fixed his mind upon (the god) Vishṇu, this lofty standard of the divine Vishnu was set up on the hill (called) Vishnupada.

Some years later V.A. Smith came out with the following free translation:

> This lofty standard of the divine Vishnu was erected on Mount Vishnupada by King Chandra, whose thoughts were devoted in faith to Vishnu. The beauty of that king's countenance was as that of the full moon *(chandra)*; by him, with his own arm, sole world-wide

dominion was acquired and long held; and although, as if wearied, he has in bodily form quit this earth, and passed to the other-world country won by his merit, yet, like the embers of a quenched fire in a great forest, the glow of his foe-destroying energy quits not the earth; by the breezes of his prowess the southern ocean is still perfumed; by him, having crossed the seven mouths of the Indus, were the Vahlikas vanquished in battle; and when, warring in the Vaṅga countries, he breasted and destroyed the enemies confederate against him, fame was inscribed on (the) arm by his sword.

Variations in the Readings

The Sanskrit text of the inscription was first published by Prinsep in 1838 and then by Daji in 1875. These readings in *Nagari* alphabet are reproduced in Fig. 5. The main difference between the two readings concerns a word in the last-but-one line, which has been read as *"Dhavena"* by Prinsep, but identified as *Bhavena* by Daji. Prinsep thought that *Dhāva* was another name of King Chandra, but most scholars now agree with Daji that the *Dha* here looks different from the five others *Dha's* in the inscription and is actually *Bha*. The error is attributed to the fact that a very slight slip of the engraver's tool is sufficient to convert the character used for *bh* into a form which may be read as *dh*. The word *Bhava* meaning *Bhakti* or "devotion" fits in better here than *Dhāva*, which means "cleaning, washing or making bright".

In the second line of the inscription, there is a reference to the *Vahlikas* conquered by King Chandra; Prinsep read this as *"vahlika"*, but Daji thought, it was actually *"balhika"*. Scholars are now agreed that Prinsep was right in his reading.

For completeness, the Sanskrit text as given by S.R. Goyal in 1984 with transliteration in English is reproduced in Fig 6. The readings in the tablets created near the Pillar on 1 January 1903 are brought out in Plate 6.

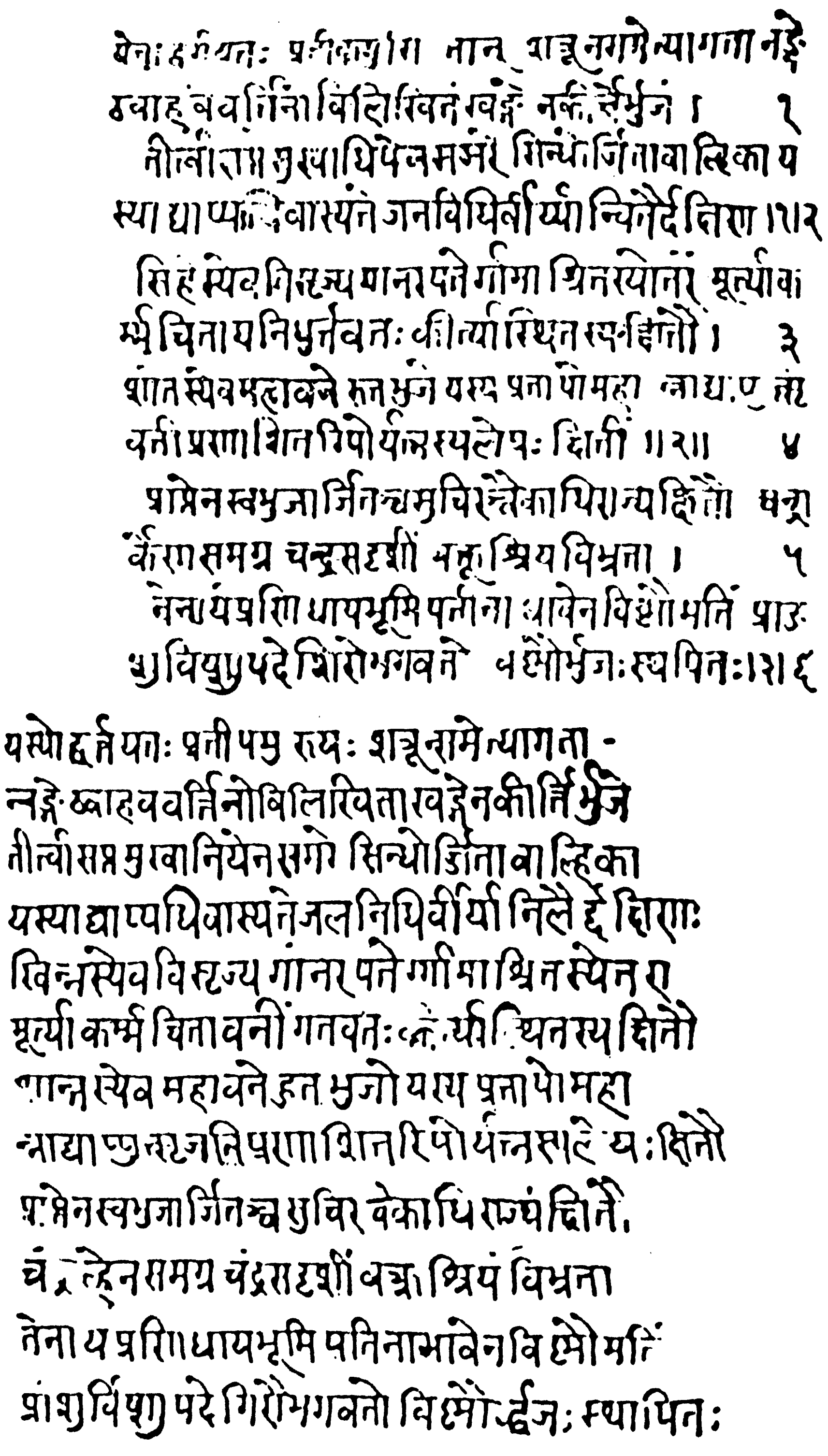

Fig. 5: Early readings of the main inscription on the Iron Pillar

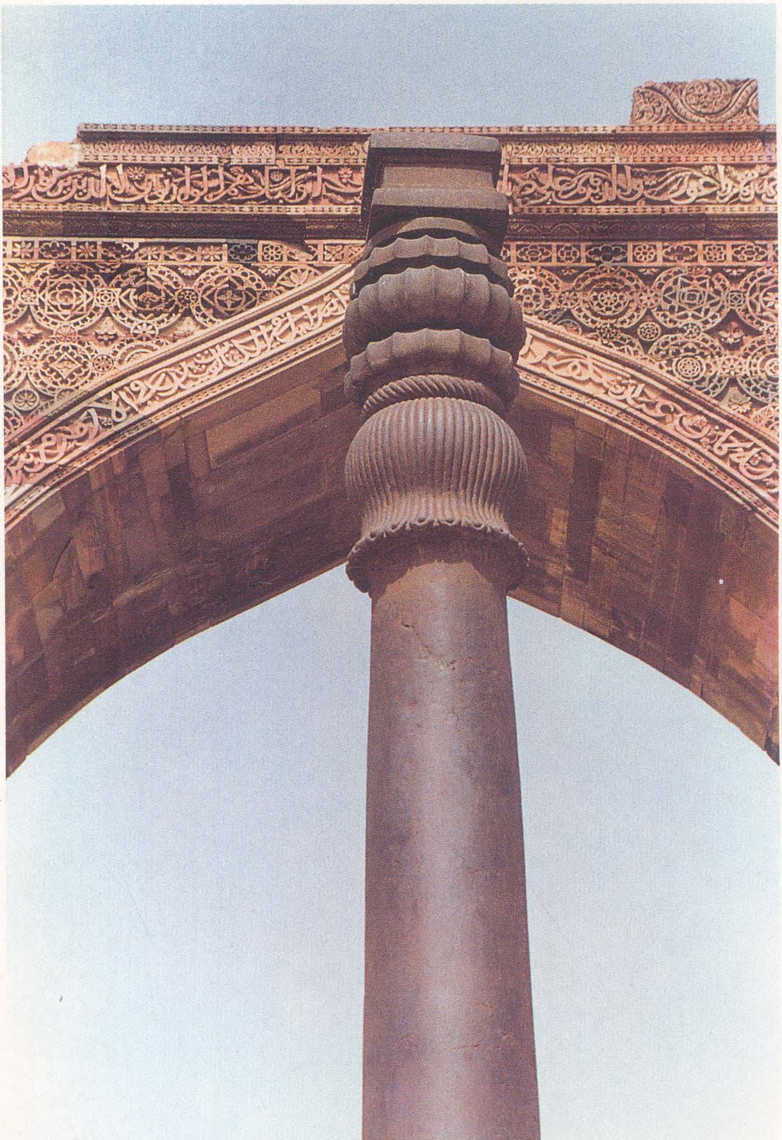

Plate 3: Top portion of the Pillar with the capital

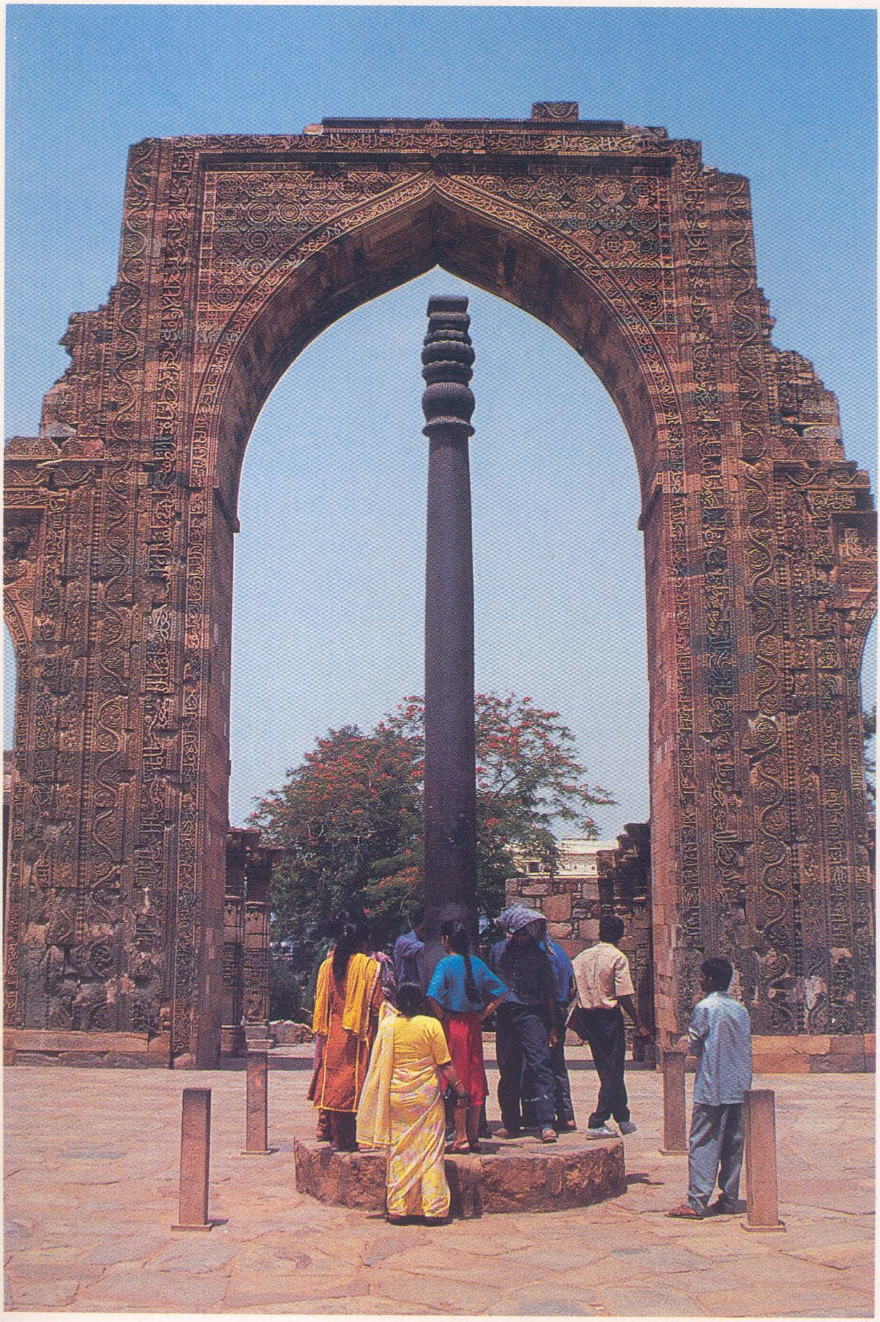

Plate 4: The Pillar with admiring tourists around

१ य[स्यो]द्वर्त्तयत: प्रतीपमु[र]सा शत्रून्समेत्यागता-
न्वङ्गेष्वाहव-वर्त्तिनो(ऽ*)भिलिखिता खड्गेन कीर्त्ति[र्भु]जे (।*)
२ तीर्त्वा सप्त मुखानि येन [स] म[रे]सिन्धोर्ज्जिता[वा]ह्लिका
यस्याद्याप्यधिवास्यते जलनिधिर्व्वीर्य्यानिलैर्द्दक्षिण: (।।*) १
३ [खि]न्नस्येव विसृज्य गां नरपतेर्ग्गामाश्रितस्येतरां
मूर्त्या कर्म्म-जितावनिं गतवत: कीर्त्या स्थितस्य क्षितौ (।*)
४ शान्तस्येव महावने हुतभुजो यस्य प्रतापो महा-
न्नाद्याप्युत्सृजति प्रणाशित-रिपोर्य्यत्नस्य शेष: क्षितिम् (।।*) २
५ प्राप्तेन स्व-भुजार्ज्जितञ्च सुचिरञ्चैकाधिराज्यं क्षितौ
चन्द्राह्वेन समग्र-चन्द्र-[स]दृशीं वक्त्र-श्रियं बिभ्रता (।*)
६ तेनायं प्रणिधाय भूमि-पतिना भावेन विष्णौ मतिं
प्रांशुर्विष्णुपदे गि[रौ] भगवतो विष्णोर्ध्वज: स्थापित: (।।*) ३

[Metre: *Śārdūlavikrīḍita* throughout]

1 [Yasy=ō]dvarttayataḥ pratīpam-urasā śattrūn-samēty-āgatān-
v[aṅ]gēshv-āhava-varttinō-bhilikhitā khaḍgēna kīrttir-bhu[ja]jē [|*]
2 tīrtvā sapta mukhāni yēna samarē Sindhōr-jjitā Vāhlikā yasy-
ā[dy]-āpy-adhivāsyatē jalanidhir-vvīryy-ānilair-ddakshiṇaḥ [||1*]
3 Khinnasy-ēva visṛjya gāṁ narapatēr-ggām-āśritasy-ētarāṁ
mūrt[t*]yā ka[r]mma-jit-āvaniṁ gatavataḥ kīrt[t*]yā sthitasya
kshitau [|*]
4 śāntasy-ēva mahāvanē hutabhujō yasya pratāpō mahān-n-ādy-
āpy-utsṛjati praṇāśita-ripōr-yyatnasya śēshaḥ kshitim [|| 2*]
5 Prāptēna sva-bhuj-ārjjitañ-cha suchirañ-ch-aikādhirājyaṁ
kshitau Chandr-āhvēna samagra-chandra-sadṛśīṁ vaktra-
śriyaṁ bibhratā [|*]
6 tēn-āyaṁ praṇidhāya bhūmipatinā dhāvēna Vishṇō matiṁ
prāṁśur-Vishṇupadē girau bhagavatō Vishṇōr-dhvajaḥ
sthāpitaḥ [|| 3*]

Fig. 6: Goyal's version of the Mehrauli Prasasti and its transliteration in English

Other Inscriptions

There are many inscriptions done during later years on the Iron Pillar. Surprisingly, the earliest of these dates from A.D. 1052, i.e., at least 600 years *after* the first inscription eulogizing King Chandra. Smith was of the view even in 1897 that the Iron Pillar was originally erected somewhere else, perhaps near Mathura, and transferred to its present site in the 11th century. He also refers as "a verified and certain fact" that one Anaṅga Pāla built old Delhi, i.e., a town in or near Rai Pithaura's Fort, including a group of richly decorated temples, in the middle of the eleventh century. He considers it "a reasonable inference" that this Anaṅga Pāla himself set up the Iron Pillar at its present location and recorded on it the year of his founding the city viz., A.D. 1052, through a short epigraph. Thus there is still considerable uncertainty about the original location of the pillar and its history over a period of six centuries.

Of the other inscriptions, one is a short Persian epigraph dated A.D. 1556 and records the name of a certain Ali Asghar Husain, son of Israil. Two others in *Nāgari* characters are dated A.D. 1515 and A.D. 1523, but supply no information of any value. The remaining three inscriptions which are also written in Hindi are, however, not without some historical importance. One of them is incised on the south-east face of the Pillar, four feet above the top of the platform. It consists of six lines and records that on Saturday, the 13th of the black fortnight of Kuvar *(Aśvin),* in the *Samvat* year 1767 (A.D. 1710) Mahārājādhirāja the illustrious Durgarjan Singh, the Budela, i.e., Bandella Raja of Chanderi, who was the son of Durga Singh, who was the maternal grandson *(nāti)* of the illustrious Raja Devi Singh, came here, and adds a wish that his salutations may reach any Raja who may visit this place. The inscription was written by one Tribhuvanarai. Then follows the name of a certain Indrajit of Sultanpur, who might have carried out the engraving of the epigraph. It would have been interesting to know the purpose of this Prince's visit to old Delhi, but no mention is made of it. Incidentally, a *Nāgari* inscription dated in the *Samvat* year 1789 (A.D. 1732) carved on the Narghati at Deogarh

in Uttar Pradesh records the name of the same prince and his genealogy.

The other inscriptions are carved side by side on the south-east face of the Pillar, the major part of the left hand record being enclosed in a line. The latter epigraph, already referred to, begins with the words *Samvat Dhilli 1109 Aṁgapāla vadi*, and to judge from the form of its characters must have been engraved in the year mentioned in it, viz. A.D. 1052, The rest of the writing, though it appears at first sight to be a direct continuation of the earlier portion, was actually done 774 years later in date and records the visit of Chatra Singhji Chauhan in *Samvat* 1883 (A.D.1826) . The information recorded is to the effect that Prithviraj flourished in *Samvat* 1151 (A.D.1094) and that in the 23rd generation from him was descended the illustrious Maharavaji Chatra Singhji. The other inscription states that in *Samvat* 419 (A.D. 362) there was a Raja, a scion of Tuvar (Tomar) race named Aṁgapāla, and in *Samvat* 648 (A.D. 591) there exists a certain Vasudeva Chauhan Raja Indra. In the 21st generation from the latter was Prithiraja in *Samvat* 1151 (A.D.1094) and in the 28th generation from him Raja Chatrasingh in *Samvat* 1888 (A.D.1831). The only fact of any value supplied by these confusing inscriptions is the date of *Samvat* 1109 (A.D.1052) for Anaṅga Pāla. The rest of the information having been recorded in the year 1827 and 1832 A.D. from memory is incorrect.

* * *

Chapter III

HISTORY AND ARCHAEOLOGY

As many a historian from the West has remarked, the intellectuals of the Indian subcontinent do not seem to have displayed, until recently, a keen sense *for* history, despite their stupendous scholastic and artistic achievements in various other spheres, which often *made* history. Indian literature, extensive and valuable as it is, particularly in the Sanskrit language, contains scarcely any work of a *purely historical* character. For a trustworthy chronology of ancient and medieval India, the scholars have had to depend heavily on the testimony of coins and inscriptions. When the latter are not available, as in regard to the very early Indian history, the researchers fall back on conjectures and inferences, which are, of course, liable to be modified or are disproved by later discoveries.

India owes to Sir William Jones, the English scholar and savant, the identification of Sandrakottos or Sandrokoptos of the Greek writers as Chandragupta Maurya, founder of the Maurya dynasty of Indian kings and grandfather of the one and only Emperor Ashoka. The outside termini for the establishment of the Maurya dynasty of Pataliputra are the years 320 B.C. and 310 B.C., but historical evidence has, on the whole, is inclined to favour the year 315 B.C. This crucial date has provided a starting point from which, with the aid of Buddhist and Sinhalese records eked out by *Pāurāṇic* traditions, it has been possible for historians to reconstruct with some degree of success an outline of North Indian history between 600 B.C. and 300 B.C. All the same, there are minor uncertainties about some important dates, as in regard to the birth and death of the illustrious Sākya Muni, Gautama Buddha, celebrated the world over as "the Light of Asia."

For the long intervening period between Emperor Ashoka and the Moslem invasions i.e., 200 B.C. to A.D. 1000, the historians have had to depend almost entirely on the coins and inscriptions unearthed by archaeologists. Occasionally, some information could be obtained from the notices of contemporary travellers and writers, native as well as foreign, and the trustworthy materials of local chroniclers, as in Kashmir and Gujarat. This is the period with which the Iron Pillar at Delhi and the inscriptions on King Chandra are concerned.

From early, fourth Century A.D. when Chandra Gupta I ushered in the "golden age" of the Guptas, coins and inscriptions on stone and metals available become much more numerous than in previous centuries. Ever since the first epigraphical and numismatic discoveries of the so-called "Orientalists" around mid-nineteenth century, the importance of items such as coins, pillars, edicts and inscriptions for the elucidation and reconstruction of Indian history has been well recognized. Subjected also to the critical and scientific methods of modern research, such discoveries have yielded a harvest of results undreamt of by the pioneers of Oriental learning. Nor is the field anywhere near exhaustion, for scarcely a year passes without adding fresh data to our store of chronological material.

It may be mentioned here in passing that starting with the rise of the Muslim dominion in India from around A.D. 1000, a change for the better takes place in the character of the historian's sources of information. Instead of mere solitary fragments of history drawn from meagre records of inscriptions, coins, copper plates, etc., copious accounts of contemporary events become available now from the pens of historians who have at least a chronological *instinct*, even if they fail occasionally in *accuracy* of individual dates.

With regard to the literary chronology of India, our knowledge of even approximate dates is woefully vague as far as the ancient period is concerned. Thus there are ambiguities concerning the dates of literary giants such as Vālmīki, Vyāsa,

Kālidāsa, Patañjali, Bhavabhūti, and Bhartṛhari. From the seventh century A.D., however, it becomes possible through the aid of synchronism, contemporary notices and internal evidence, to fix fairly definitely the period of some of the more famous writers of the time.

It is in the backdrop of the aforementioned murky historical and archaeological scenario that we have to seek answers for questions like the following concerning the historic Iron Pillar at Delhi :

(1) How, when, where and by whom was this Pillar fabricated?

(2) Was the Pillar located in other places also, before it was installed in the present location? If so, where and when?

(3) Who is the king referred to as "Chandra" in the posthumous euology on this Pillar? Who was it that wrote or got written this three-verse *Praśasti* in Sanskrit?

(4) If another king is involved in getting this inscription written, what was his relation to King Chandra?

In searching for the answers to these questions, we come face to face with what is widely accepted as one of the most intriguing and baffling problems of ancient Indian history.

The Evidence of Palaeography

Palaeography is the modern science dealing with the study of ancient writings and inscriptions. It has now developed to such an extent that its evidence can well be clinching and final. *Epigraphy* that deals with inscriptions on stones, statues, etc., and *numismatics* that concerns itself with coins, medals, etc., may be considered as branches of palaeography.

The relevant periods with regard to the inscription on the

Delhi Pillar are as follows:

A. Before Christ:
315 B.C. to 135 B.C. (the Maurya dynasty)

B. After Christ
A.D. 75 to A.D. 225 (the Kushana dynasty)
A.D. 290 to A.D. 490 (the Gupta dynasty)

Among the many rulers of these three dynasties only the following can *possibly* stake claims for the many conquests referred to in the inscription on the Delhi Pillar:

1. 315 B.C. to 295 B.C. : Chandragupta Maurya.
2. 275 B.C. to 235 B.C. : Emperor Ashoka (Maurya).
3. A.D. 75 to A. D.110 : Kanishka (Kushana).
4. A.D. 320 to A. D. 340 : Chandra Gupta I.
5. A.D. 340 to A. D. 375 : Samudra Gupta.
6. A.D. 375 to A. D. 415 : Chandra Gupta II (Vikramaditya)

The abovementioned dates are only *approximate* and have been rounded to 5 or 0 for convenience. In regard to Samudra Gupta 's accession the dates vary between A.D. 325 and A.D. 350.

In the earliest and, in many respects, pioneering paper on palaeography published in 1838, an authority as distinguished as James Prinsep allotted the inscription on the iron pillar to the third or fourth century A.D. In 1875 Daji was inclined to assign it to a period later than the Gupta period. In his important contribution of 1887, Fleet commented on the closeness with regard to the characters of the inscriptions on the Iron Pillar at Delhi, the pillar describing Samudra Gupta's heroic exploits at Allahabad and the Kumara Gupta Pillar at Bilsad. His first impression was to identify King Chandra of the Iron Pillar with

Chandra Gupta I, the first Mahārājādhirāja of the Gupta dynasty. He also recorded the conviction of J. Ferguson that this inscription belonged to either of the two Chandraguptas of the early Gupta dynasty.

The views of many Indian researchers on this subject have been recorded in the 1989 book entitled *King Chandra and the Mehrauli Pillar* edited by M. Joshi and S.K. Gupta. A careful perusal of these views leads to the conclusion that most scholars are inclined to place this insription, on palaeographic grounds alone, along with those of Samudra Gupta and Chandra Gupta II. The assertion of G.R. Sharma in 1945, as quoted in the aforementioned book, is worth reproducing:

> The evidence of palaeography is conclusive. I have compared the Mehrauli Pillar inscription with the Kushana inscriptions on the one hand and with the Gupta inscriptions on the other... Even a glance at them reveals a wide gulf between the Kushana and Mehrauli characters and a corresponding similarity between Mehrauli and Gupta... *Therefore the Mehrauli Pillar inscription must be placed on palaeographic grounds in the first half of the fifth century.*

This book also informs us that Daji, who is among the leading writers on Indian palaeography, has no doubt that the Mehrauli *Praśasti* was written in early fifth century A.D. Thus, as Lallanji Gopal observes in the same vloume, palaeographic features do not give any chance to Chandragupta Maurya, and to accommodate Kanishka, we will have to make adjustments in his date as well as the date for the onset of the Gupta features of the *Brāhmi* script.

Another vital fact in the present discussion concerns the *posthumous* character of the inscription. Though a few scholars have tried to controvert the observation of Fleet that it is a "posthumous eulogy", a careful scrutiny of the text does not leave any scope for doubt. Verse 2 of the inscription makes a *double* reference to this fact: *firstly*, "the king has gone to the other world in bodily form" and *secondly*, "the king remains in this world in the form of his fame". Thus, it follows from the text of

the inscription itself that though the *dhvaja-stambha* or "flagstaff" for Lord Vishnu was set up by King Chandra, the inscription on it could not have been engraved during his lifetime. In all likelihood, the inscription was composed and engraved during the reign of his successor.

To sum up, the evidence of palaeographic studies seems to point to Samudra Gupta or Chandra Gupta II as the king referred to in the inscription on the Delhi Pillar. Consequently, the monarch who got the inscription composed and engraved, eulogizing his father's exploits, has to be Chandra Gupta II or Kumara Gupta I (See Table-4) respectively.

Evidence of the King's Exploits

It is obvious that whomsoever the historians may identify as "King Chandra" referred to in the inscription on the Iron Pillar, that king *has* to live up to the many heroic exploits and achievements mentioned in the *praśasti* (eulogy) on the Pillar. Most early historians have tended to give more importance to the *name* rather than to the *achievements* of this King and thus we have a surprisingly wide cleavage in the recorded views on his identity. Every early monarch, great or medium or small, whose name contained the word "*Chandra*" (meaning the moon) as a component, has been seized upon by one historian or the other. So we have this rather confusing state of affairs wherein King Chandra has been identified variously with Chandragupta Maurya, Kanishka (*"Chandra"*), Chandravarman of Pushkarana, the Nāga kings Chandrāṁśa and Sadāchandra, Chandra Gupta I, Chandra Gupta II and even Devarakshita of the Purāṇas!

During the period 1962-67, while engaged in preparing his doctorate thesis entitled *A History of the Imperial Guptas*, Goyal came forward with the interesting and original proposition that King Chandra mentioned in the Iron Pillar inscription is best identified with *Chandraprakāśa*, which is another name of the Gupta emperor Samudra Gupta. He has summarized his views in the earlier-referred book edited by Joshi and Gupta. To start

with, he points out, in agreement with Fleet, that the relevant portion of the inscription does, by no means, assert that the *original* name of the king was Chandra, the expression being "*Chandrahvena*, i.e., called Chandra." He then suggests that no king known to history of this period by the name Chandra can be given credit for the notable achievements mentioned in the inscription. We should, therefore, *reverse* the process of enquiry, start with the analysis of the *facts* recorded about him and try to identify the king who answers the description *best*, without getting unduly obsessed about the name.

The inscription supplies us the following facts about the eulogized monarch:

(i) He defeated his enemies in the *Vanga* countries.

(ii) He crossed "the seven mouths of the river Indus", i.e., the Indus delta, and conquered the *Vahlikas*.

(iii) The breezes of his prowess were still "perfuming" the regions of the southern ocean.

(iv) He established sole and supreme sovereignty on the earth by "the force of his own arm".

(v) He ruled for a long time.

(vi) He was a devout *Vaishnava* and erected this Pillar as a "*dhvajastambha*" (flagstaff), for Lord Vishnu (see Plate 7).

(vii) His fame lingered on the earth even after his death.

Agreeing with earlier scholars on the possible date of the inscription, Goyal notes that this monarch flourished either in the second half of the fourth century or in the early decades of the fifth century A.D., was simultaneously a mighty conqueror, an empire builder and a devotee of Lord Vishnu and acquired sole and supreme sovereignty by his *own* prowess and *not* as a sequel

to the power and prestige of his predecessor. "There is only one king who answers this description and he is Samudra Gupta, the real founder of the Gupta empire." Goyal is on very strong grounds in this last assertion because historians generally identify Samudra Gupta alone as "the most able soldier in a line of fighting kings", "one of the greatest rulers India has known", "hero of a hundred fights" and "the ablest and most versatile of the Guptas".

As Goyal points out, rather sarcastically, Chandra Gupta II was an empire builder only in the sense that he acquired an empire by killing his brother Rāma Gupta. His only notable military achievement was the conquest of the Śaka kingdom of western India, which, incidentally, had shrunk to a rather small size by the time he conquered it. All the same, it is extremely significant that this victory over the Śakas has not even been hinted at in the inscription on the Iron Pillar.

Goyal has further unearthed the fact that Samudra Gupta was probably known by the name Chandraprakāśa, as brought out by the following verse quoted by Vamana in his *Kāvyālaṅkārasūtravṛtti* (Circa A.D. 800) :

So-ŷam Samprati Chandraguptatanayah
Chandraprakāsó yuvā,
Jāto-bhūpatirāśrayah, krta-dhiyām
diṣṭyā-kṛtārthaśramaḥ.

The reference here is to Vasubandhu, the famous Buddhist scholar, who was the minister of "Chandraprakāśa, the son of Chandra Gupta". As much is not known of any patronage extended by Kumara Gupta, the son of Chandra Gupta II, it seems reasonable to conclude that the expression Chandraprakāśa in the above verse refers to Samudra Gupta, who was himself a poet, apart from being the son of Chandra Gupta I.

In conclusion, Goyal has noted that a few points mentioned with regard to King Chandra in the inscription on the Iron Pillar fit *both* Samudra Gupta and Chandra Gupta II. Both were

Vaishṇavas by faith and both ruled for a long period. However, the military feats, as noted in the inscription, are quite distinctive and leave no room for doubt that they fit *only* Samudra Gupta, the indomitable warrior who performed rare feats of valour during that period. As Goyal puts it: "Actually the Mehrauli *praśasti* neither records nor omits any significant fact which requires a laboured interpretation in the case of Samudra Gupta, as it does in the case of Chandra Gupta II. It merely described *mutatis mutandis* in three brief verses what the Allahabad *praśasti* says in 33 long lines."

To sum up, the historical evidence definitely narrows down the identification of the king eulogized in the inscription on the Delhi Iron Pillar to either of the two great monarchs of the Gupta period, viz., Samudra Gupta or Chandra Gupta II. Until about 30 years ago, the so-called Chandra-Chandra Gupta II equation was accepted, by and large, by historians, but Goyal's study proposing the Chandra-Samudra Gupta equation has been increasingly favoured in the last two decades by scholars and researchers in the field. Since the inscription obviously constitutes a *posthumous* eulogy, another monarch, possibly the son, i.e., either Chandra Gupta II or Kumara Gupta I, got the inscription incised on the Pillar.

On internal evidence, the Iron Pillar is neither a "*vijaya-stambha*" (pillar of victory) nor a "*kīrti-stambha*" (pillar of fame). It is actually a "*dhvaja-stambha*" (symbolic flagstaff) of Lord Vishnu and hence, in all likelihood, was installed originally in a Vishnu temple and, as per general tradition, without any inscription. As Smith surmises, the *Viṣṇupāda-Giri* (Mount of Vishnu's feet) referred to as the location for the Pillar in the inscription could well have been in Mathura, the city presently just 80 miles from Delhi and well-known as a site for Vishnu temples from time immemorial. This ancient pilgrim centre, which has many hills and mounds in or adjoining the city precincts, was well within the boundary of the Gupta empire and has also thrown up some stone inscriptions relating to the Gupta period. The choice of *iron* and not the traditional stone for the Pillar strongly suggests a tough soldier and warrior behind the fabrication of

the Pillar, and, not so much a great Patron of arts and letters. On this ground also, Samudra Gupta seems to have an edge over Chandra Gupta II as the builder of the Pillar. The three Sanskrit *slokas* mentioned in the inscription can definitely be associated with Chandra Gupta II, the grateful son of a great warrior-father and an acknowledged patron of great Sanskrit poets.

Uniqueness of the Iron Pillar

Apart from its ingenious mode of fabrication and astonishing resistance to corrosion, which have captured the imagination of scientists and technologists and will be discussed at length in the chapters that follow, the Delhi Pillar displays a few unique features, which ought to be of special interest to historians and archaeologists.

A passing reference has been made earlier to the use of iron for this "*dhavaja-stambha*" (flagstaff) in a temple dedicated to Lord Vishnu. Stone or wood would normally have been used, but the choice of a metal and, that too, iron is definitely unusual. This significant feature can only be associated with a great warrior and a specialist in weapons made of iron and goes naturally with the "hero of a hundred fights", namely, Samudra Gupta. The engraving of an eulogy (*praśasti*) depicting a human being's exploits on the flagstaff of any temple dedicated to a god or deity is also unusual. In this case, the engraving was obviously due to a person *other than the one* who got the Pillar fabricated and might well have been done *after* this unconventional flagstaff had to be shifted from the temple for pressing reasons, for instance, because, of strong objections from priests and scholars (after Samudra Gupta's passing way) to the placement of a then not-so-auspicious metal such as iron in a holy place.

Another unique feature of the Iron Pillar is that it has really no parallel as far as the history of the Indian subcontinent is concerned. Except for the Dhar Iron Pillar of the eleventh century, now lying in three broken parts, all *iron* objects unearthed from earlier or later periods come nowhere near the celebrated Delhi Pillar with respect to cross-section and mass, leave alone its enigmatic rustlessness despite centuries of exposure to the open

atmosphere. It has to be admitted, however, that such uniqueness applies equally to a few other marvellous monuments of our country such as the magnificent Brihadeeswara Temple built at Thanjavur, Tamil Nadu, in the south, by King Rajaraja Chola in the tenth century and the matchless Taj Mahal built at Agra, Uttar Pradesh, in the north by the Moghul Emperor Shāhjahān in the seventeenth century. There may be some other examples too, but in these two cases, efforts were made by the respective sons and successors, viz., King Rajendra Chola and Emperor Aurangzeb, to build similar, if not more impressive, monuments at Gangaikondacholapuram and Aurangabad, respectively. Both failed in their efforts. In fact, it is more often than not a chance combination of many favourable circumstances like an imaginative royal patron, a novel and original concept, an indomitable will to create something great, a host of skilful artisans led by an inspired leader and the availability of the required funds and materials, that leads to the construction of unique monuments without parallel like the Delhi Pillar, the Thanjavur temple and the Agra memorial.

A brief description of the Dhar Iron Pillar would be appropriate here. Attributed to the period of King Bhoja (A.D. 1000-1055) and perhaps built as a "*vijaya-stambha*" (pillar of victory), this very tall Pillar was also made of wrought iron and its three broken parts are to be found today in the Lat Masjid area of Dhar near Indore, Madhya Pradesh. Its cross-section is non-uniform, mostly square, but occasionally rectangular or octagonal, and much less than that of the Delhi Pillar. However, it is much taller and even a little heavier than its Mehrauli counterpart. Its total height obtained by adding the lengths of its broken pieces comes to 43' 8" (nearly 14 metres). While the weight of the three pieces together worked out to slightly over seven tonnes. It has been hailed as the tallest pillar of its kind, not only in ancient India, but also in the entire ancient world. To quote the eminent historian, Vincent Smith:

> While we marvel at the skill shown by the ancient artificers in forging the great mass of the Delhi Pillar, we must give a still greater measure of admiration to the forgotten craftsmen who dealt so successfully in producing the still more ponderous iron mass of the Dhar Pillar monument.

* * *

Chapter IV

EVOLUTION OF IRON TECHNOLOGY

Utkhātam Nidhi-Śankhaya Kṣiti-talam
Dhmātā-Girer-Dhātavo...

The surface of the earth was dug up in the hope of wealth and the ores on the mountain were smelted ...

So begins a verse of the celebrated poet, Bhartṛhari, the author of the popular *Śataka-Trayam* (Three Centuries of Verses), who is supposed to have lived some time in the seventh century A.D. This quotation strongly suggests that even scholars in our country were aware of the strides made in technology during or before their times. In metallurgy, the smelting of metalliferous ores to produce molten metals constitutes an important technological step. Not surprisingly, progress in this technology was gradual and halting, starting naturally with low-melting metals and progressing steadily to the high-melting ores. Table 5 gives the melting points of some selected metals and one can get a rough idea of the temperatures that have to be reached and consequently the difficulties, from a technological point of view, in producing these metals from their ores.

In passing, it is relevant to mention that today all metals, even with very high melting points, are extracted in accordance with the technological requirements of different countries through ingenious, modern techniques developed by chemical metallurgists during this century. In India too chemical and metallur-gical engineers have done their country proud through their commendable efforts during the last four decades to develop

Table 5 : Melting points of some selected metals

Sl.No.	Name of metal	Symbol	Melting point (in °C)
1.	Aluminium	Al	660
2.	Beryllium	Be	1280
3.	Copper	Cu	1085
4.	Gold	Au	1064
5.	Iron	Fe	1535
6.	Lead	Pb	327
7.	Magnesium	Mg	650
8.	Mercury	Hg	- 39
9.	Molybdenum	Mo	2626
10.	Nickel	Ni	1455
11.	Platinum	Pt	1769
12.	Silver	Ag	962
13.	Tantalum	Ta	2996
14.	Thorium	Th	1750
15.	Tin	Sn	232
16.	Titanium	Ti	1660
17.	Tungsten	W	3410
18.	Uranium	U	1132
19.	Zinc	Zn	420
20.	Zirconium	Zr	1852

appropriate extraction techniques and to produce indigenously all strategic metals and alloys needed for the fast-growing defence, nuclear and aerospace programmes at the national level. Scientists and technologists of the Bhabha Atomic Research Centre, Mumbai (Bombay), and the Defence Metallurgical Research Laboratory, Hyderabad, have been in the forefront in this challenging task and their purposeful researches and devlopmental work have enabled India to meet its requirements for high melting metals like beryllium, molybdenum, tantalum, titanium, tungsten and zirconium.

What is metallurgy? This word is defined in the *Oxford English Dictionary* as "the art of working metals, comprising the separation of them from other matters in the ore, smelting and

Plate 5: Detail of the Pillar's surface showing the excellent state of preservation of the inscription

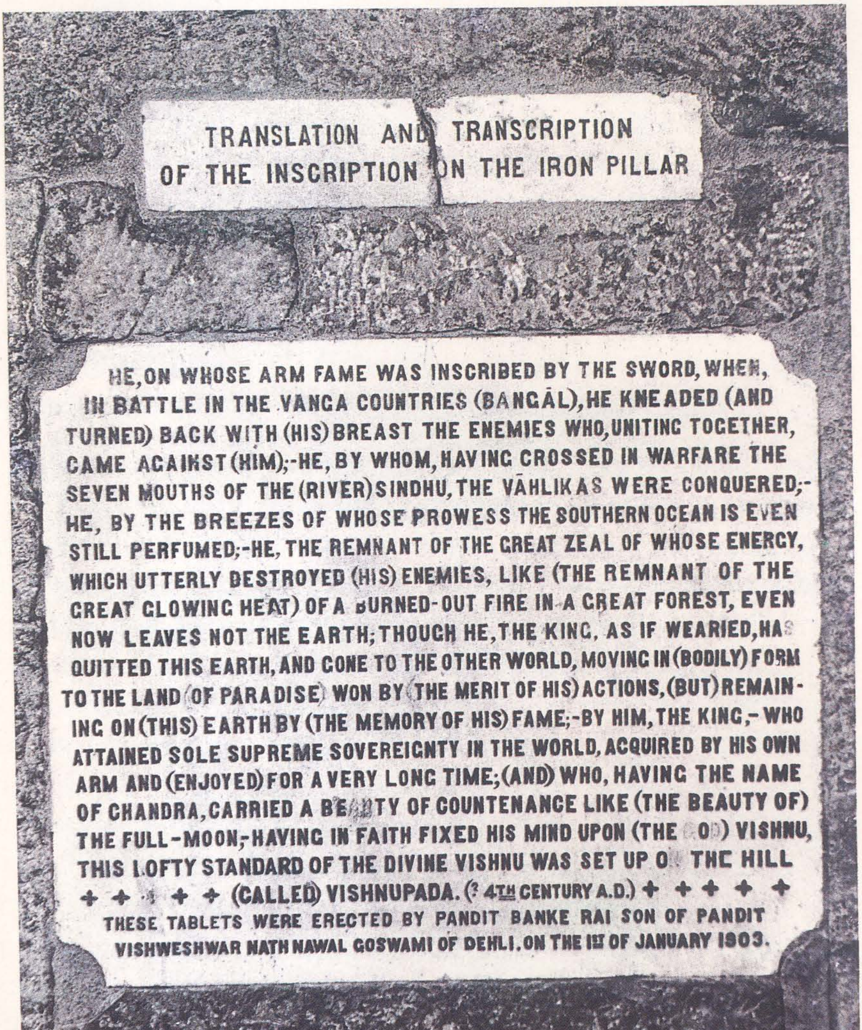

Plate 6: Tablets erected in 1903 near the Pillar with transcription and translation of the Sanskrit inscription

refining." The history of this art which later evolved into the science and technology of metals, as we understand it today, stretches back over at least 10,000 years. Metals in so many forms are so much a part of our every-day life and environment that it is almost impossible for us to imagine the world of the Stone Age man and the times when the knowledge and use of metals were completely absent. The ascent of human civilization is today classified by progress from the Stone Age to the Chalcolithic (copper-stone) Age, then to the Bronze Age and finally to the Iron Age. As usual with such broad classifications, there are no firm dividing lines and certainly no universal chronology. Here one should consider the onset of the Bronze Age in Mesopotamia in the fourth millennium B.C. and the survival of the Stone Age in the twentieth century in the aboriginal lands of Australia!

How did metal working arise? Most metals occur in the earth's crust in the form of their ores, i.e., as chemical compounds such as oxides, sulphides or carbonates. Therefore, techniques for their recognition *(prospecting)*, extraction from their surroundings *(mining)* and then chemical separation to produce the metals themselves *(smelting)* had to be devised before they could be fashioned into desired forms *(working)*. There are, however, some metals such as gold and copper, that occur free or in the elemental form, even though in small quantities and, generally, in quite isolated locations. One can visualize a Stone Age man finding by accident a nugget of gold, bright and yellow, and hammering this unusual, new-found "stone" with his stone hammer to see how it broke. Since gold would have flattened instead of breaking, he would have been fascinated and, perhaps, worked it down to a shape to suit his or his beloved's fancy!

Was copper or gold the first metal to be worked by man? The answer to this question becomes complicated by the fact that gold seems always to have been highly valued and the chances of gold artifacts surviving in the *original* form are rather remote *vis-á-vis* the more mundane copper. As a historian of metallurgy has put it: "Gold survives in countless transformations. In fact, it is not far-fetched to speculate that at least part of the gold in the filling of a modern tooth may once have been part of a comb that gleamed in the hair of an Egyptian princess."

Extraction of Iron from its Ores

Iron (Fe) is the fourth most abundant element present in the earth's crust, representing slightly over 5 per cent of the lithosphere. It is also an important constituent element, sometimes unwanted, in hundreds of minerals. It readily combines with carbon dioxide, oxygen, sulphur or silica to form carbonates, oxides, sulphides or silicates, and only very rarely occurs as the native element, chiefly in meteorites and basalts. Iron is an important element in sedimentary, igneous and metamorphic rocks and gives many surface materials on the earth a red, reddish-brown, brown or yellow colour, characteristic of its compounds, particularly oxides.

Iron-bearing materials in deposits which are of sufficient size and have enough iron content to be either used or potentially used as *commercial* sources of iron are termed *iron ores*. The vast majority of iron ore bodies are composed of iron oxides in the minerals goethite ($Fe_2O_3.H_2O$), hematite (Fe_2O_3) or magnetite (Fe_3O_4) with lesser amounts of other iron minerals. In some parts of the world, particularly Canada, deposits of the mineral siderite ($FeCO_3$) are mined as iron ore.

Natural, merchantable iron ores of high quality generally contain 55-68 per cent Fe on a dry-analysis basis with low phosphorus and other impurity levels. Such ores are extracted on a large-scale in Australia, Brazil, India, Liberia, Mauritania, South Africa, some regions of the erstwhile USSR and Venezuela. In France and Luxemburg iron ores with 32-38 per cent Fe are commercially exploited with success because of their location very near the steel works. Enrichment of lean iron ores, as found in the USA, Canada, China, Norway and Sweden is also common today using a variety of process technologies.

After mastering the art of extracting copper from its ores and also that of casting different copper alloys, particularly the bronzes, the metal worker of the Bronze Age obviously faced some difficulties in obtaining iron in its metallic form from the ores. In this connection it is worth observing (see Table 5) that pure iron

: and even the most impure cast iron needs a vell over 1200°C to get melted and become free-here was no possibility of producing *liquid* iron al copper-smelting process. Further, even the ; difficult to work on and smith effectively when ; heating and then forging. So a completely new :alled for and seems to have been successfully nastered some time after 1500 B.C., even though ·ouded in mystery.

chnique evolved further in due course of time and ʼn as the "bloomery process". Here, the iron ore ting it with charcoal in a furnace blown by bellows. ɔloom" thus produced generally consists of a mass iron particles, surrounded by, and intermingled ɔduced during the smelting process. The metal is ıt hot, pasty state to produce a solid mass of iron, ıe time, expelling the bulk of the unwanted slag. ɔrocess was to become a standard one for iron urvive, with minor modifications mainly in the ı, for almost 3000 years. The first people renowned s in the making of iron were the Hittites of Asia ll-known, their superiority on the *battlefield*, as ssyrians who took over their skills, was due to the :ir weapons over those of their contemporaries.

ology of the various phases of metal-making ıg activities is quite complex, partly because of the idence and partly because of the rather late ritten record on the scene. All the same, some the progress in metal working can be obtained ig.7.

ıce Revolution

n iron-making was brought about in the fifteenth introduction of the so-called "*blast furnace*" for ˘ iron ore. Here again, there is a divergence of ether or not this was an independent development.

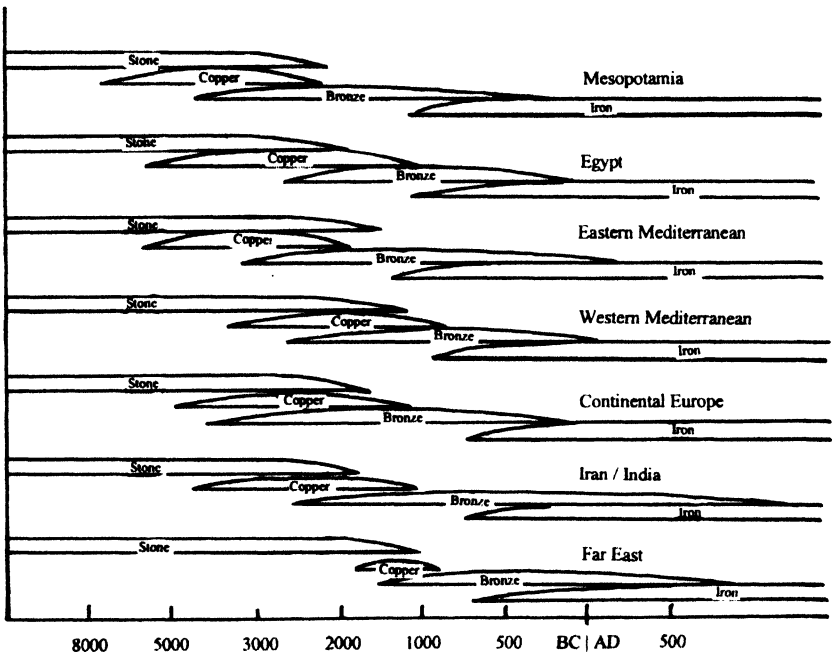

Fig. 7: National time chart showing rise of metalworking in the old world (based on Hawkes 1976)

established trading contacts between the East and the West. The prowess of the Orientals, in particular the Chinese, in the production of large iron castings was well-known at that time. Further, the steady improvements in the European bloomery process had led to the erection of rather tall furnaces with bellows actuated by water wheels. The next step, i.e., from this medieval high-shaft bloomery, from which the bloom was taken out for hammering, to the blast furnace where the molten iron could flow out was relatively small. The latter made use of a *deeper* bed of charcoal and a *more powerful* blast to give a *longer* dwell time to the iron in contact with the carbon at a *higher* temperature, say, 1300-1350°C as against 1150-1200°C in the bloomery.

The effect of this change from the bloomery to the blast furnace was truly revolutionary. The iron, instead of remaining as a conglomeration of small particles of the more or less pure metal in the bloom would now absorb carbon to the extent of 3-4 per cent, lowering in that process its melting point from over 1500°C to less than 1200°C. Along with this *liquid* metal there would be a liquid slag floating on top of the metal, which could be run off from time to time, while sufficient metal got collected in the hearth for the purpose on hand. When eventually run out and allowed to solidify, the metal containing so much carbon in it would be brittle and impossible to forge even when hot! Therefore, the need to remelt and refine the iron would arise, leading to the many significant developments leading to modern steel technology. The period from 1850 to 1880 is considered by historians of metallurgy as the most revolutionary period for the steel industry since it witnessed the remarkable inventions of Bessemer, Siemens and Thomas in western Europe, ushering in the era of cheap bulk steel through the so-called converters and open hearth furnaces.

Figures 8 and 9 respectively illustrate a sixteenth century bloomery (or bloomsmithy) and a modern twentieth century blast furnace, highlighting the tremendous advances in size and sophistication over four centuries. Today a blast furnace can produce anywhere between 2000 and 10000 tonnes of iron *per day*. In spite of many new technological developments during this century, it looks as though the annual global demand for iron (of

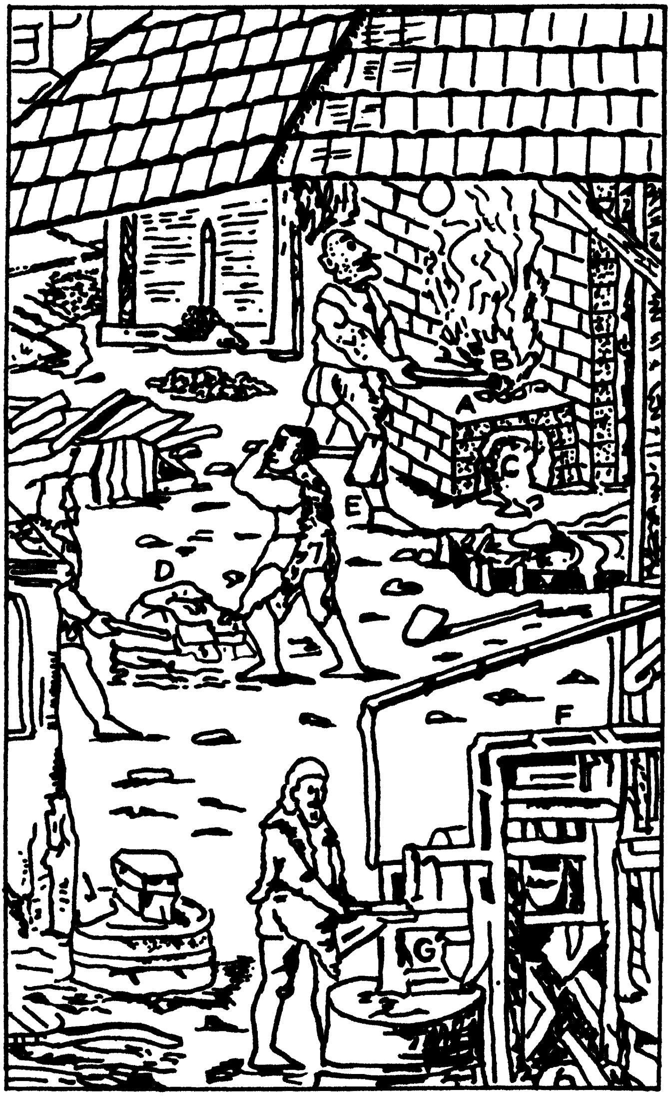

Fig. 8: An artist's view of a sixteenth century iron forge (bloomsmithy)

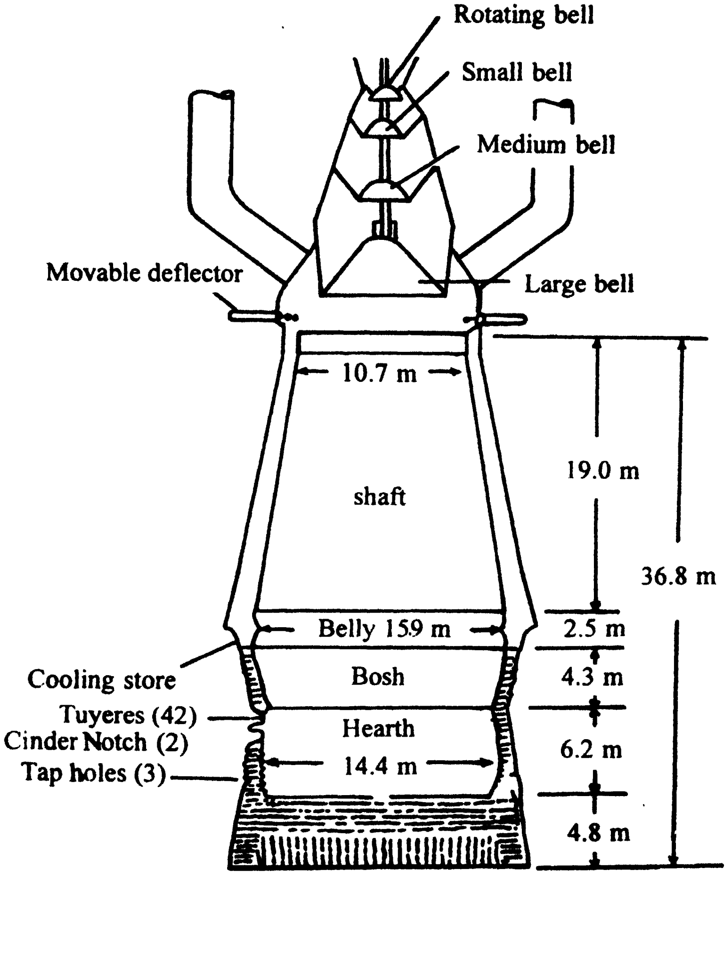

Fig. 9: Features and approximate dimensions of a modern blast furnace

over 500 million tonnes) will be met *primarily* by the blast furnace process even in the early years of the next millennium.

Iron Technology in Ancient India

Notwithstanding the existence of many conflicting views on the antiquity of iron or the advent of the Iron Age in the Indian subcontinent, it is generally conceded by all modern scientists and scholars that India's *most significant* contributions to ancient metallurgy have been in the field of iron and steel. Archaeological findings of the last three decades have thrown fresh light on the growth of iron technology in ancient India and there is now fairly clear evidence (according to B. Prakash and V. Tripathi) indicating the presence of iron on the Subcontinent as early as around *1300 B.C.* Thus, the earlier theories and suggestions that iron technology was brought from the West Asian countries to India stand discounted. As A.K. Biswas asserts in his 1991 study on "Minerals and Metals of Ancient India", the presence of *indigenous* iron has now been established around the twelfth century B.C. in *three* geographical contexts *far removed* from each other and, therefore, the diffusionist theory concerning Hittite or Aryan influence should be dismissed as far-fetched.

K.N.P. Rao has highlighted, in recent articles, the fact that the megalithic culture dated around the period from 1200 B.C. to A.D. 200 has been closely associated with iron. Archaeological evidence suggests quite strongly that iron was being made during this period all over the Indian subcontinent, from Kanyakumari to Kashmir and even in the North West Frontier Province, now part of Pakistan. This is by no means surprising since iron ore is found all over the subcontinent and parallel growth of cultures and technologies is bound to occur.

Some of the important archaeological sites in India associated with the Iron Age culture have been documented by Prakash and Tripathi and are shown in Fig. 10. These scientists have found it useful to divide the early Iron Age cultures of India into five zones viz., north-western (A), north (B), north-eastern (C), central (D) and peninsular (E). Although the C-14 or radio carbon dates are not fully relied upon by some investigators,

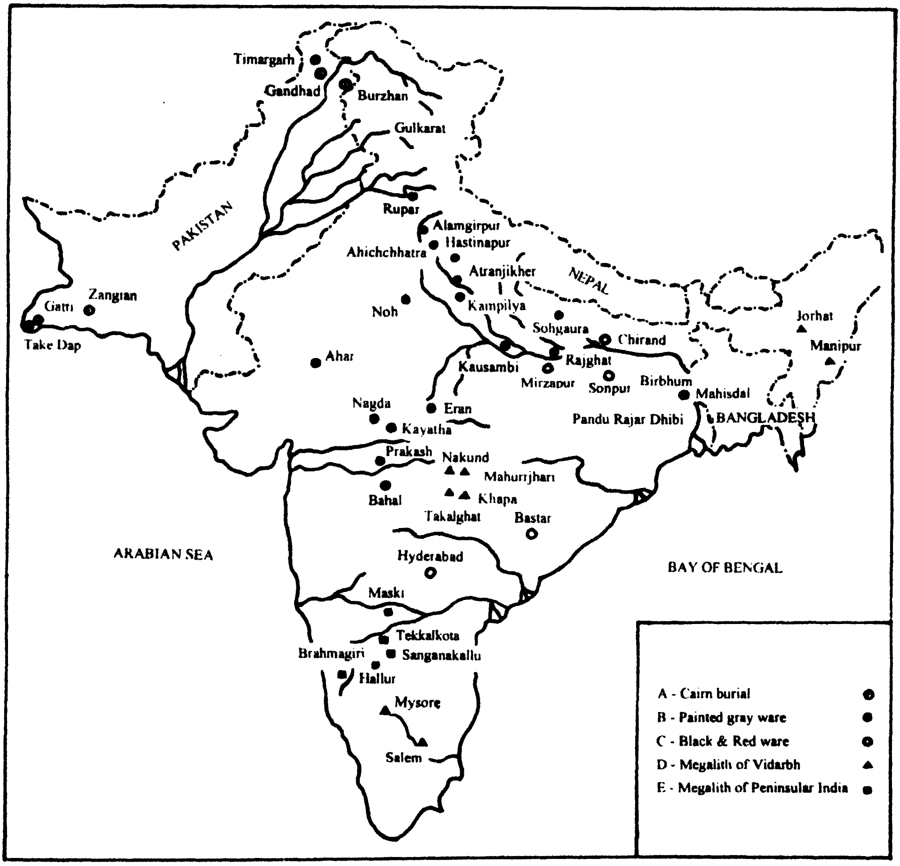

Fig. 10: Map of Indian subcontinent showing the archaeological sites where Iron Age articles have been found

have associated, on this basis, broad dates with each excavation site, as given in Fig. 11. A detailed analysis of the various tools and other iron objects found in the five cultural zones is presented in Table 6. It is interesting to record here that a majority of the iron tools and artifacts unearthed at these places have mostly been from burial sites and rather rarely from sites of habitation (villages). Further, ethnological studies of primitive or tribal societies in the states of Bihar, Orissa and Madhya Pradesh suggest that iron-making was practised as religious or secret rituals by *Asuras* (demons or outcasts) rather than by the farming tribes.

Iron Objects in Different Cultural Zones

Dates recorded for recently excavated iron objects by the radio carbon technique (using the radioactive C-14 isotope of carbon) extend all the way from 1400 B.C. to A.D. 1000.

In *Zone A* i.e., once north-western India (present-day Pakistan) the Zhob and Loralai areas of Baluchistan have yielded ancient iron objects in what are known as "Cairn burial sites". Similar burial sites have been excavated in adjoining areas of Iran as well. In the Swat Valley, the Gandhara grave culture has revealed the presence of iron in ancient burial sites, dated around 800 B.C. This period seems to be closely associated with grey-coloured pottery, some of which has been dated around 900 B.C., and is quite different from the grey ware of other cultural zones.

In *Zone B,* i.e., North India, the vast Gangetic basin is associated with its "painted grey ware" (PGW) culture that seems to have flourished from 1000 B.C. to 400 B.C. This zone extends from Punjab and Himachal Pradesh in the north to Ujjain in the south and from the great Indian desert of Bikaner in the west to Kausambi and Vaisali in the east. Although PGW gives this culture its name, it constitutes only a small percentage of the pottery excavated from this large area. Other wares include the well-known northern black polished ware (NBPW or simply NBP), plain grey ware and red ware. Although they did not use coinage or writing, the PGW settlements demonstrate a trend towards growing

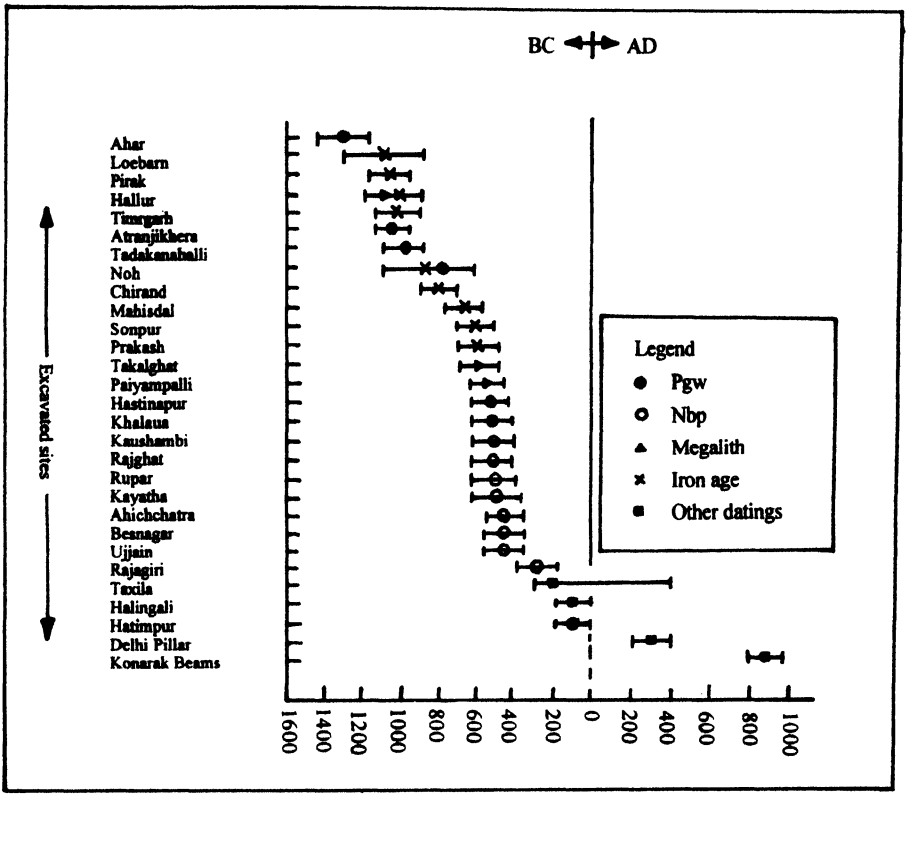

Fig. 11: Radio carbon dates of Iron Age sites indicating the phased deve- -lopment of Iron technology in India (Half-life equal to 5730 years)

Table 6 : Distribution of tool types in different zones of ancient India.

	Zone A	Zone B	ZoneC	Zone D	Zone E
Arrowheads	●	●	●	●	●
Axes		●			
Blades		●	●		●
Bangles				●	
Clamps			●		●
Chisels				●	
Cauldrons				●	
Daggers	●				●
Ferrules					●
Fish hooks				●	
Hoops	●				
Horse bits			●		●
Hooks					●
Knives	●	●	●		●
Nails		●	●		
Points		●			
Pins		●			
Rings			●		
Sword blades	●	●	●	●	●
Swords				●	
Scrapers	●				
Spear heads		●			●
Socketed tangs		●			
Sickles		●			
Spikes			●		
Socketed-on leaf-shaped shafts			●		
Tangs	●				

technological expertise in glass and iron, even though the iron objects display some similarity with those of Zone A. One of the important sites of this Zone is Atranjikhera with a C-14 dating of 1125 B.C.

Zone C, i.e., north-eastern India, is referred to as the "black and red ware" (BRW) zone and adjoins Zone B, extending over eastern Uttar Pradesh, Bihar and parts of Madhya Pradesh and Maharashtra. The BRW culture is roughly dated as around 800 B.C. - 700 B.C. and is noted for its quite distinct local characteristics.

In *Zone D,* i.e., Central India consisting of Vidarbha and adjoining regions of Maharashtra, iron appears in megalithic burials with black and red ware quite different from and more sophisticated than those of Zone C. Dated around 700 B.C. the excavated iron objects show an orientation towards war weaponry. The most important find of this region is the *megalithic iron melting furnace* at Naikund dated 700 B.C., complete with air-injecting tuyeres and slag flowing out of a hole, as illustrated in Fig. 12.

Zone E, i.e., peninsular India, consisting of the South Indian states of Karnataka, Kerala, Tamil Nadu and Andhra Pradesh, is characterized by black and red ware of the post-neolithic phase. The recent excavations at Hallur, Tadakanhalli and Paiyampalli suggest that this zonal culture using iron flourished from 1200 B.C. onwards.

In *all* the afore-mentioned five cultural zones, iron had obviously made its appearance between 1000 B.C. and 800 B.C. The Iron Age itself might have begun in India still earlier, if one can accept the iron dating of 1300 B.C. associated with the excavations at Ahar and Gufkral in Zone B and A respectively. Ahar as well as Noh, also in Zone B and with a carbon dating of 1200-1100 B.C., lie in copper-rich areas with ancient copper-smelting traditions. Pasty, sponge iron might well have been produced accidentally during melting of copper in these places and then developed intentionally for eventual production and use.

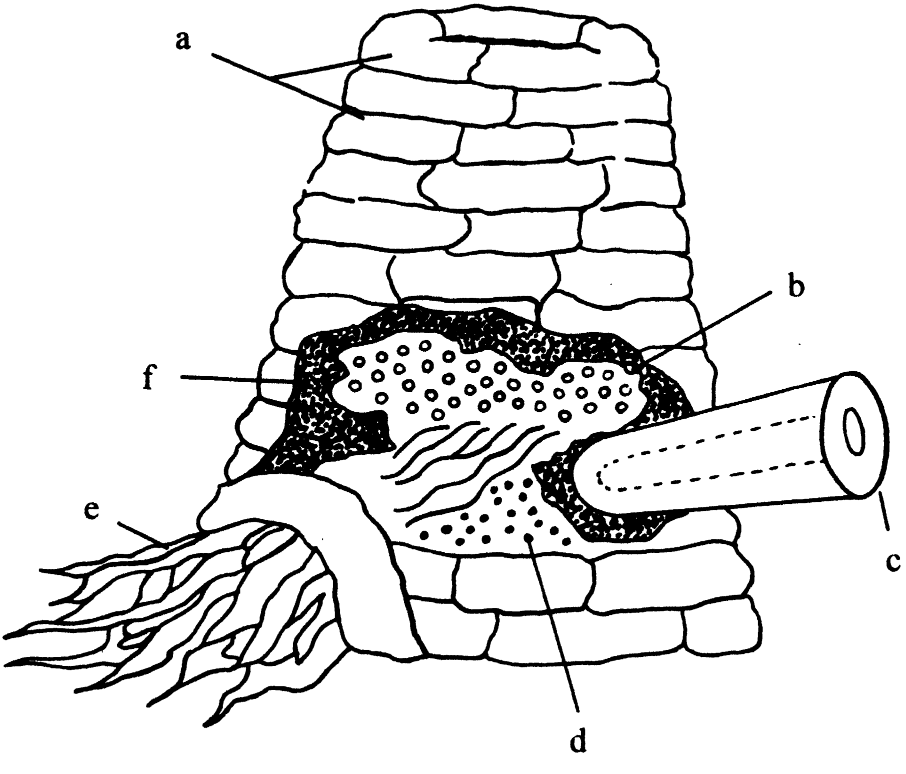

Fig. 12: Megalithic iron melting furnace reconstructed from the evidence obtained at Naikund (700 B.C.)

Culturally, all these five zones had their own distinctive features, but few common traits, except for Zones B and C which display comparable old pottery and other antiquities. This cultural dissimilarity strongly suggests that iron technology actually developed *independently* in the differnt centres of these Zones. The abundance of the iron oxide ore in *all these areas* is a point worth noting in this connection.

The fact that iron was, with only a few exceptions, in full use in the *entire* subcontinent by 1000-800 B.C. lends strong support to the theory of *independent* and *indigenous* development of iron technology in India. Obviously, its diffusion over such a vast area like India's in a short period is far from feasible. Diversities in the cultural milieu of the above-mentioned zones also strongly support this *parallel* development theory.

Growth of Indigenous Iron Technology

Once the initial discovery of iron had been made, and its superior qualities appreciated, one can easily imagine the inevitable and persistent growth in its technology over the next several centuries to meet the needs of steady urbanization and increasing sophistication in the living styles of the people. With the availability of better quality iron and with increasing skill in making steels, there was a rapid widening of the field of applications, from simple hunting tools to weapons of war, to agricutural implements and even domestic objects and appliances.

The steady growth of indigenous iron technology has been dealt with by Prakash and Tripathi as pertaining to three stages or periods, viz., the Early Stage of 1200 B.C. - 600 B.C.; Middle Stage of 600 B.C. - 100 B.C.; and Late Stage of 100 B.C. - A.D. 600. Table 7 lists the tools, implements and other objects appearing in these three stages.

In the *early stage* (1200-600 B.C.) the use of iron was obviously restricted to simple tools, particularly hunting tools such as spearheads, arrows, points, socketed tangs and blades. A few

Table 7 : Various tools and implements appearing at the three stages of Iorn Technology growth.

●: Definite existence ○: Non-existence □: Confirmed data not available.

Tool type	Type name of tool	Early stage	Middle stage	Late stage
Hunting tools	Spear heads	●	●	●
	Arrow heads	●	●	●
	Points	●	□	□
	Socketed tangs	●	□	□
	Blades	●	●	□
	Spear lances	□	●	□
	Daggers	□	●	●
	Swords	□	●	●
	Elephant goads	○	●	●
	Lances	○	○	●
	Armours	○	○	●
	Helmets	○	○	●
	Horse bits	○	○	●
	Caltrops	○	○	●
Agricultural tools	Axes	●	●	●
	Sickles	●	●	●
	Spades	○	●	□
	Ploughshare	○	●	□
	Hoes	○	●	●
	Chisels	○	●	●
	Picks	○	□	●
Household objects	Knives	●	●	●
	Tongs	●	□	□
	Discs	○	●	□
	Rings	○	●	□
	Spoons	○	●	●
	Sieves	○	○	●
	Cauldrons	○	○	●
	Bowls	○	○	●
	Dishes	○	○	●

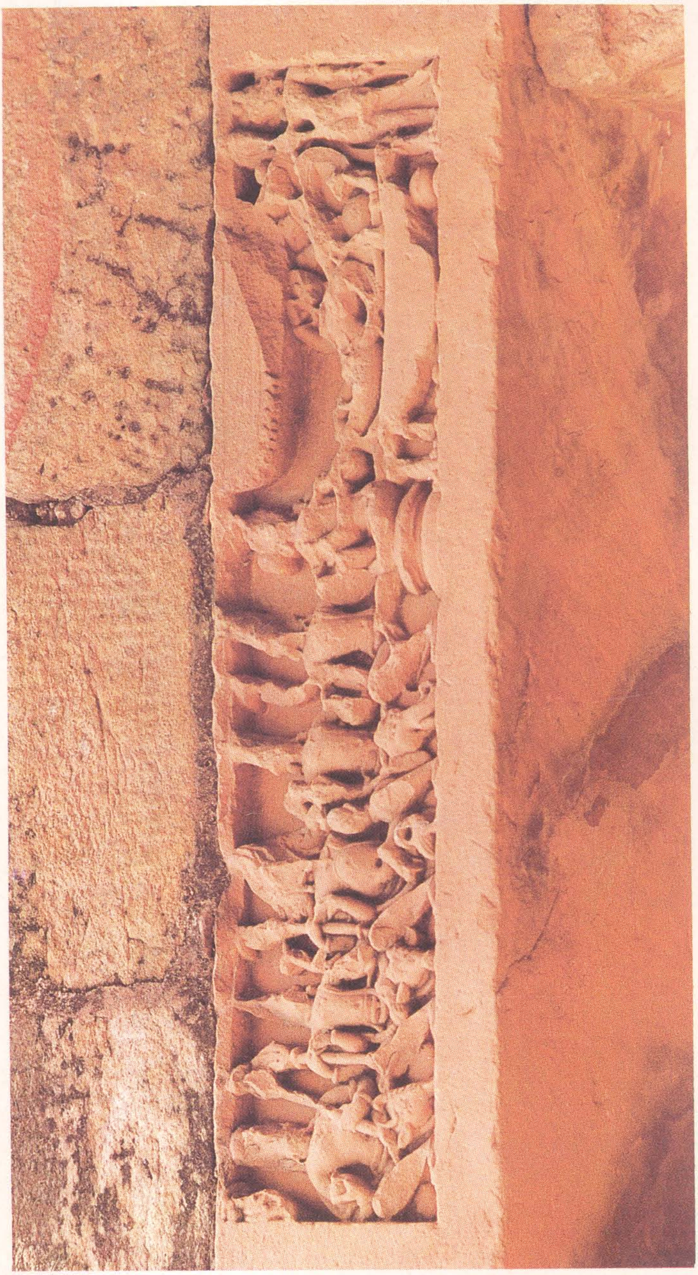

Plate 7: A damaged piece of sculpture near the Pillar showing Lord Vishnu in his famous reclining position

Table : 7 (Contd.)

Tool type	Type name of tool	Early stage	Middle stage	Late stage
Building materials	Rods	●	□	□
	Pins	●	□	□
	Nails	●	●	●
	Clamps	●	●	●
	Pipes	○	●	□
	Sockets	○	●	□
	Plumb bobs	○	●	□
	Chains	○	●	●
	Door hooks	○	●	□
	Door handles	○	○	●
	Hinges	○	○	●
	Spikes	○	○	●
	Tweezers	○	○	●
	Anvils	○	○	●
	Hammers	○	○	●
	Scissors	○	○	●
	Saws	○	○	●

sickles and axes used in agriculture and some domestic items such as knives and needles have also been associated with this period. Small rods, pins, nails, etc., that could have been used in construction work during this period have also been unearthed.

The *middle stage* (600-100 B.C.) seems to have been a period of tremendous expansion in the use of iron. There was a profusion of newer and more effective war weapons such as single- and double-tanged arrowheads, javelins, spears, lances, dagger blades, swords and even elephant goads. Numerous agricultural tools of this period such as sickles, spades, hoes, ploughshares and axes have been located at many sites. Also rather rare household items such as knives, discs, rings, spoons and saucepans have been found. The unearthed clamps, pipes, sockets, chisels, chains, door-hooks, etc., testify to diverse constructional uses.

The *late stage* (100 B.C. - A.D. 600) witnessed many peaks in iron technology, including the great Iron Pillar at Delhi. The Kushan empire and the Gupta empire which flourished during this period reveal the diverse innovative skills of craftsmen who obviously enjoyed royal patronage. A large number of new weapons for use in both war and hunting have been unearthed in Taxila, one of the key sites of this period. Swords, javelins, armour, helmets, shield bases and elephant goads belong to Taxila of this period, as also hoes, spades, sickles, shovels and weeding forks used in agricultural operations. Other objects such as knives, ladles, spoons, sieves, saucepans, cauldrons, saucers and tripods were used in households during this period. In the Gupta period, in response to the needs of kings, nobles and chieftains, palaces and fortresses were built with larger quantities of iron in the form of nails, clamps, staples, sheets, door handles, spikes, etc.

Ferrous Physical Metallurgy : A Brief Overview

It is necessary at this stage to understand and appreciate some elements of modern physical metallurgy, i.e., the science that deals with metals and alloys, their structure and properties. To start with, *pure metals* are often commercially and technologically unimportant because of their rather poor *mechanical* properties such as hardness and strength. *Alloys*, which are metallic materials made up of more than one chemical element, dominate the engineering and technological fields because of their *superior* properties which can be further improved or optimized through proper design and processing. Based on a well-known metal, a commercial alloy or a series of alloys often acquires its own special or trade name. For example, brasses and bronzes are alloys of copper, while steels and cast irons are alloys of iron.

Purity is a relative concept. "Two nines", i.e., 99 per cent, may be considered quite pure in some cases, but "three nines" and "four nines", i.e., 99.9 per cent and 99.99 per cent, may be a must for some metals. For example, copper and aluminium have to be obtained close to the "three nines" purity for applications based on their high electrical and thermal conductivities. In recent decades there has been a demand for *very pure* or *ultrapure*

metals for special purposes, including research. Since refining to a high degree of purity is generally a complicated and expensive process, very pure metals are produced only on small scales, usually in grams or kilograms. By contrast, a single blast furnace may produce upto 10,000 tonnes of *iron* per day, while an open hearth furnace may turn out over 1000 tonnes of *steel* per day, even while controlling an impurity like sulphur to less than 100 ppm (parts per million)! In passing, a reference may be made to the highest-purity industrial process of this century, viz., "zone refining" for semiconductor silicon, that dominates the computer and media scenes today with impurity levels of *less than 1 ppm* !

Pure iron has somewhat poor mechanical properties. In fact, a specimen of iron of "three-nines" purity can be cut through with a strong, sharp stainless steel blade! Alloys of iron containing carbon *upto 2.0 per cent* (generally less than 1.0 per cent) along with still smaller percentages of other elements, particularly manganese and silicon, sometimes unwanted, but yet creeping in during the process of manufacture, are referred to as steels and can develop very good *mechanical* properties through appropriate thermal and mechanical treatments. Alloys of iron containing *more than 2 per cent* (often even more) carbon, again along with some other elements, particularly silicon in the 1.0 - 3.0 per cent range, are referred to as cast irons and can be readily melted and cast into intricate shapes with many useful properties.

Ferrous physical metallurgy is that branch of physical metallurgy which is concerned with the design and processing of steels or cast irons having desired properties. The design process consists of selecting appropriate alloying additions and processing procedures to produce microstructures that will result in the required physical, chemical, mechanical and other properties. The alloying elements in case of iron are very many, the *major* ones being carbon, manganese, silicon, nickel, chromium, molybdenum, aluminium and boron. There are also *micro alloying* elements such as niobium, titanium and vanadium, which are added upto 0.2 per cent for achieving very special properties. *Impurity* elements to be avoided or controlled

include sulphur, phosphorus, oxygen, nitrogen and hydrogen, the last three being gases. The modern processing procedures include melting, refining, casting, hot-rolling, cold-rolling, annealing, hardening, heat treament and thermo-mechanical treatment. Microstructural aspects examined under the optical microscope up to a magnification of around 1000 include the grain size of the *primary* phase, the size, amount, distribution and composition of *secondary* phases and possible segregation of *minor or impurity* phases at grain boundaries. Thus the design of steels and cast irons involves, in the modern context, a complicated interplay among alloying, processing and micro-structural elements. The bulk of the scientific principles, correlations and thumb rules in this area have been developed and tested only during the last 150 years, particularly after the Second World War (1939 - 1945).

* * *

Chapter V

MODE OF FABRICATION

In the light of the foregoing information on iron technology particularly in ancient India, it becomes possible now to approach the problem of mode of fabrication of the famous Iron Pillar at Delhi. Relevant facts and figures, including detailed of chemical analysis of samples taken from different parts the Pillar, have earlier been presented in Chapter I. Here, the metallurgical studies of the Pillar undertaken during the period 1962 - 1992 will be examined critically for relevant data that can throw light on the techniques used for the production of iron and for the fabrication therefrom of the Pillar. In this connection special mention deserves to be made of the welcome initiative of the Metals Research Committee of the Council of Scientific and Industrial Research (CSIR), New Delhi, to sponsor in the early sixties some research projects devoted to the Delhi Iron Pillar, as also to the so-called Ādivāsi Iron still produced by age-old processes in the jungles and underdeveloped areas of Orissa and Madhya Pradesh. Thus scientists and technologists of independent India could enter into a field of research that was until then, by and large, the exclusive preserve of Western investigators.

Scientific Observations

In their oft-quoted work entitled *The Delhi Pillar: A Study of Corrosion Aspects*, the British scientists W.E. Bardgett and J.F. Stanners reported in 1963 that it was highly unlikely that the iron of the Pillar was ever in the molten state and, further, the heterogeneous nature of the structure shows that no heat

treatment was ever applied. The last stage in the construction of so large a piece of iron so far back in time would almost certainly have consisted of the hammer-forging together of balls of hot iron and a continuous hammering process to create a smooth surface. *During the considerable time needed to complete this process*, an oxide film would have been formed and got hammered into the surface. Slag, too, would have been incorporated in the scale.

Following elaborate and systematic chemical, spectrochemical, X-ray and microscopic as well as mechanical studies of the Iron Pillar and other not so ancient iron relics from Konarak in Orissa, Sultanganj near Delhi and Sinhabad from Maharashtra, M.K. Ghosh came to several interesting conclusions in his trail-blazing paper of 1963 entitled "The Delhi Iron Pillar and its Iron." He found that the chemical composition and the general microstructure of the Pillar iron and of different irons made in primitive Indian furnaces over the centuries were quite similar, but the properties of the Pillar iron are somewhat different, obviously due to very heavy mechanical working. The following were his other conclusions, which applied, in his opinion, to most ancient iron samples:

1. The Pillar iron is heterogeneous in structure.

2. The composition of the Pillar iron is comparable to that of a modern low-carbon steel.

3. The Pillar is forge-welded, and quite effectively too.

4. While manganese is practically absent in the Pillar iron, the phosphorus content is high.

Another work during the same year by Lahiri, Banerjee and Nijhawan is entitled "Some Observations on the Corrosion Resistance of Ancient Delhi Iron Pillar and Present-time Ādivasi Iron made by Primitive Methods." The detailed metallurgical examination and corrosion studies described in this publication confirm earlier findings and lead to the conclusion that the high

corrosion resistance of the Delhi Pillar is related to the mode of smelting and fabrication employed, particularly the trapping of slag in sponge iron during smelting and their intimate kneading with each other during the subsequent forging operation.

Fabrication of the Pillar

The comprehensive review article by G. Wranglen of the Royal Institute of Technology, Stockholm, entitled *The 'Rustless' Iron Pillar at Delhi* was published in 1970. This scientist was of the view that the material of the Pillar was wrought (i.e., worked) iron and had never been molten. The iron ore, perhaps weathered magnetite, was obtained by surface quarrying and was bedded intermittently with charcoal in a small charcoal-fired furnace with a foot-driven hide-bellow. The hot lumps of iron sponge thus obtained were hammer-forged in order to squeeze out most of the slag. Judging from the weld-lines visible on the surface, the Delhi Pillar seems to have been built up from a great many lumps, weighing 20-30 kg each, successfully forge-welded together under firing with a charcoal blast. The surface of the Pillar still retains marks of hammer blows.

The question has been raised by many as to how long it would have taken the blacksmiths of those days to forge this magnificent pillar weighing more than six tonnes. Assuming that the furnaces of that period could produce only 20-30 kg of pasty sponge iron in one heat (i.e., extraction operation) lasting a few hours, some 250-300 heats would have been necessary to produce the iron needed for hot forging and shaping the pillar. With ten furnaces operating in tandem and each producing two heats every working day, it would have taken at least two weeks to obtain the iron required to forge the pillar. At ten workers per furnace and at least a dozen labourers for hammering, over 120 craftsmen and labourers would well have been on the job for a fortnight and more, that would have been needed to complete this most unusual and undoubtedly pioneering project. Led obviously by a highly knowledgeable master blacksmith, the craftsmen had acquired mastery even in that age over the intricate engineering operation and technological control

of furnace that were necessary to repeatedly produce iron of a reasonably uniform composition.

In his article "Early Metallurgy in India" (published in 1984) R.F. Tylecote of the Historical Metallurgy Society, Great Britain, reports how the blacksmiths of Aligarh replied to a question put to them by a British traveller in 1924 on the making of the Delhi Pillar. This reply is worth quoting in full:

> Having procured an immense quantity of exceedingly pure Gwalior ore, which could be reduced to pure iron or mild steel by simply heating the blocks of ore in the presence of charcoal and hammering them into billets, they would have proceeded to the site chosen for the Pillar. Having made a hole in the ground, they would have piled in a quantity of ore and placed a mass of kindled charcoal fire over it directing the blast on to it by placing 6 or 8 pairs of native bellows with the nozzles converging on to the centre of the mass. A few feet away on one side they would then have prepared a similar hole and repeated the process so that there were two masses of white-hot native iron close to one another. When these were at the welding temperature the surface charcoal would have been swept away. By levers the second mass would have been turned over on top of the first mass and then hammered down until it welded itself on to it.
>
> More "pancakes" having been welded on in the same manner, they would have trimmed the rough exterior with chisels and then fitted the earth again upto the level of the large mass so obtained. Thus they would have continued to forge and weld on these thin sheets, raising after each addition the level of the earth so that the new 'pancake' was a little above the level of the forged mass. Thus would the Pillar have been built up eventually, as we now know it. Finally the whole of the outside would have been pared down with cold chisels to a true cylindrical surface.

This mode of fabrication seems very plausible and had, in fact, been suggested in Great Britain for the Chedworth, Catterick and Corbridge beams. Rao has illustrated his review article (published in 1991) with an artist's impression of this mode of forging of the Pillar, which is given in Fig. 13 with some minor modifications.

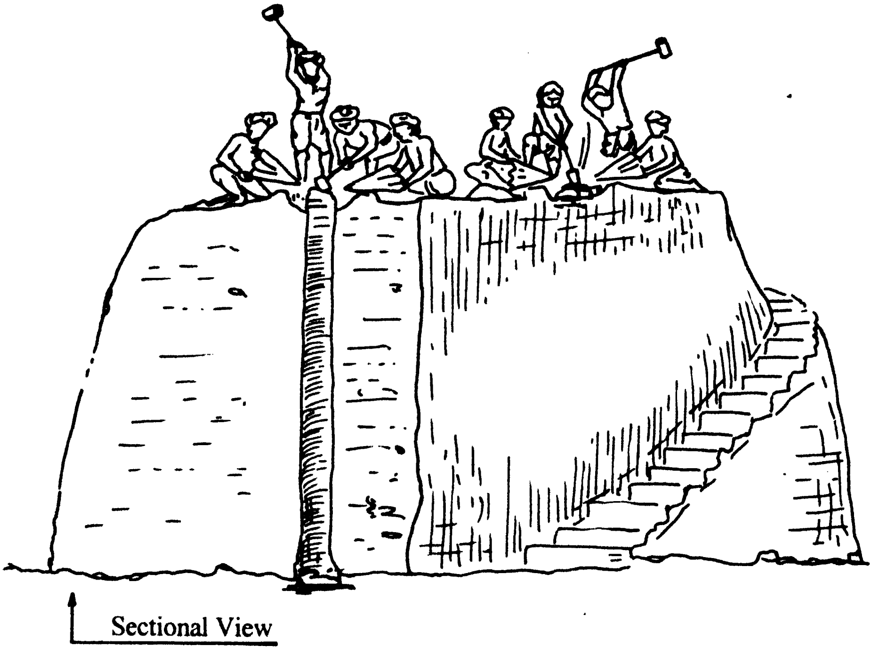

Fig. 13: Forging the Iron Pillar–An artist's impression

Indian Studies

In 1988 B.B. Lal prepared a long review on the Delhi Pillar which was published in 1989. This review is largely based on the studies carried out by him in the early sixties as Chief Archaeological Chemist of the Archaeological Survey of India. He also opines, on the basis of metallographic examination, that the Delhi Iron Pillar was not cast, but fabricated by forging and hammer-welding lumps, balls or discs of hot pasty iron in a step-by-step process.

In 1989, for the first time, the pulse echo method of ultrasonic non-destructive testing (NDT) was utilized to study the Delhi Pillar by a team headed by V. Bindal of the National Physical Laboratory, New Delhi. High voltage (about 400 volt) pulses of short duration were applied to transducer probe heads which converted the electrical pulses into ultrasonic pulses with the help of an ultrasonic flaw detector. Any crack, void or discontinuity would behave as an interface between two media and reflect the ultrasonic waves. The grain boundaries in the iron of the Pillar would also scatter the ultrasonic waves in random directions, provided the grain size was larger than the wavelength of the ultrasonic beam. Eventually, the ultrasonic energy would be converted into electrical pulses and the signals would be displayed, after suitable amplification and rectification, on the cathode ray screen of the ultrasonic flaw detector. Using this sophisticated NDT method, the Delhi scientists confirmed that the Pillar had a heterogeneous structure and the variation in structure from one location to another was rather large. The grain structure was established as coarse and there was no indication of the presence of any large void or discontinuity inside the Pillar.

Drawing on recent information provided on the reduction of magnetite (Fe_3O_4), R.K. Dubey of the Indian Institute of Technology, Kanpur, has suggested in his 1990 paper on "Aspects of Powder Technology in Ancient and Medieval India" that sponge iron pieces obtained by charcoal reduction of iron ore would, in fact, be agglomerates of reduced iron particles

containing a large amount of porosity. He considers it reasonable to conclude that the Delhi Iron Pillar was made by successive hot forging of directly reduced sponge iron blocks in a die. This procedure is rather similar to current powder forging techniques, with the difference that the latter is not usually used to make elongated items by joining pieces together. One may even say that the ancient Indians combined in one process, the modern powder production, powder consolidation and sintering steps through their "preforms" directly from the iron ore.

Two long authoritative reviews, one by B. Prakash and V. Tripathi (1986) of the Banaras Hindu University, Varanasi, and the other by A.K. Biswas (1991) of the Indian Institute of Technology, Kanpur, deal with ancient Indian metallurgy in general, but devote considerable space and attention to the famous Iron Pillar. While the Varanasi scientists wonder whether the "pancake" forging technique would have been feasible for an iron pillar of such a large size, the Kanpur scientist agrees with the earlier suggestions and concludes that forge-welding has indeed been the technique used to fabricate the Delhi Pillar. As he puts it, the Iron Pillar was built up from a great many lumps, weighing 20-30 kg each, which were successfully forge-welded together under firing from a charcoal blast. The existence of weldlines and hammer blow marks on the Pillar surface confirm this view. Heavy mechanical working is also attested to, by the measured high density, low porosity, slip lines in the microstructure and nearly identical yield point and maximum strength of the Pillar iron. Biswas opines that the quality of forge welding of the Delhi Pillar was of a high order and definitely far superior to that of the much later Konarak beams.

* * *

Chapter VI

CORROSION RESISTANCE

The Iron Pillar at Delhi has been an object of perennial interest and curiosity not only for the common people, but also for knowledgeable persons, particularly chemists and metallurgists, for two main reasons. First of all, there has been the curiosity with regard to the metal-producing and metal-working aspect, i.e., the technology by which a metallic object of such a large size and mass could be fashioned so many centuries ago. Secondly, there has been the sense of wonder on how this metallurgical marvel had survived in this remarkably well-preserved condition in spite of continuous exposure to the open atmosphere for over fifteen centuries. The former aspect has been dealt with in the previous chapter. The unbelievable corrosion resistance of what many have referred to as "the rustless wonder" will be discussed in the following paragraphs.

It is by no means surprising that numerous explanations have been put forward during this century to account for the extraordinary and somewhat puzzling resistance to rusting of the Delhi Pillar despite its exposure to sun and rain, heat and cold, for hundreds of years. Most of the explanations have been widely discussed and, more often than not, criticized and even dismissed as "unlikely", "misguiding", "imaginary", "unbelievable", "untenable" etc. Some of the theories on the Pillar's corrosion resistance are based on sundry considerations such as its position and appearance, the practice of rituals leading to an oily surface and the application of some ancient *lepa* (coating) for preservation from rust and decay. Other more scientific approaches are based on climatic and environmental factors, method or technique of fabrication, the presence of a

protective oxide layer, the massiveness of the structure, heat capacity considerations, special surface features involving slag and inclusions, the orientation of the Pillar, duration of its wetness and dryness and the high purity of the metal, particularly its freedom from manganese and its high phosphorus content. Before one can critically examine these ingenious explanations or theories concerning the so-called "rustlessness" of the Delhi Pillar, it is necessary to understand the basic elements of corrosion science, which has made considerable progress during this century. Metallic corrosion has, in fact, been an important academic discipline and a fascinating area of research for some decades now.

Corrosion is scientifically defined as "the degradative interaction of a material with its environment." Although usually applied to metals and metallic materials (i.e., alloys of various types such as steels, cast irons, brasses and bronzes) the term may also be applied to other materials, particularly inorganic substances such as stone, brick and concrete. It is also relevant to mention here that corrosion is only one of a *number* of degradation mechanisms that affect materials in use. Others that are fairly widely known and discussed in scientific and technological literature are wear, fatigue, fracture, ultraviolet degradation, oxidation, mildew and rot. These degradative processes cause the users of durable goods to incur costs (sometimes very high) for their maintenance, repair and early replacement. On a global level, these costs have a tremendous economic effect in that they represent considerable resources in the form of materials, capital, energy and labour, all of which, in the absence of these degradative and consequently, destructive effects, could be beneficially employed for other purposes.

Corrosion and, more specifically, metallic corrosion, is a phenomenon for which a number of studies have been carried out in various countries and the losses or costs thereof determined at the national level. To give an example, the National Bureau of Standards (NBS), USA, reported in 1978 to the US Congress, after an exhaustive study by experts, that about 70 billion US dollars representing over 4 per cent of the gross

national product (GNP) were used up or lost in 1975 because of corrosion. These experts also stated that 0.7 per cent of the GNP of these expenditures could have been *avoided.* Even allowing for some uncertainties in this study, it becomes quite obvious from the data that continued development of more effective corrosion-control technology, and its more widespread application can cut down corrosion and reduce these costs appreciably.

The consequences of corrosion are, however, not limited to economic losses. They also involve health (as in metallic implants in the body), safety (as in the failure of vehicles and structures) and technology (as a developmental barrier to new techniques). Thus, studies in corrosion have acquired considerable importance, particularly from the practical points of view of its prevention and control.

Rusting of Iron and Steel

As mentioned in the Prologue, iron and steel are the most commonly used engineering metals and constitute a far greater tonnage than all the other metals put together. Many industrial processes involve the handling of strong, i.e., highly acidic or caustic, chemicals. Iron or steel becomes suitable for such applications only when protected by surface coatings (metallic, organic or cementitious), or if heavily alloyed, as in the case of stainless steels which contain a minimum of 11 per cent chromium. These are, however, *specialized* applications. The main environments to which iron and steel get normally exposed are the *natural* ones of air, water and soil. It is now well-recognized that the rate of corrosion of unalloyed iron and steel is primarily determined by the aggressiveness of the environment, the variations in microstructure and composition having a much smaller effect.

All chemical reactions causing metallic corrosion are now known to involve the transfer of electrons *(negatively* charged particles with the symbol e^-) and metallic ions (metallic atoms *positively* charged consequent on the release of electrons from them) across charged interfaces. One of the reactants, the

electron, can move with little energy loss from distant points within the metal. It is apparent, therefore, that the transformations leading to corrosion are of an *electrochemical* nature and hence corrosion processes are best explained and understood on the basis of electrochemical theories.

The mechanism of corrosion of iron and steel, commonly known as *rusting*, involves the dissolution at the so-called *anodic* sites on the metal surface, the reaction generally depicted by the simple equation:

$$Fe \longrightarrow Fe^{2+} + 2\,e^{-}$$

Natural environments are usually almost neutral, i.e., neither acidic nor alkaline, or slightly alkaline, and under these circumstances, the balancing so-called *cathodic* reaction is:

$$O_2 + 2\,H_2O + 4e^{-} \longrightarrow 4OH$$

This electrochemical process is illustrated in Fig.14.

The essential point to note is that corrosion of iron and steel can only occur when *both* oxygen and water (or high humidity) are present simultaneously in the environment to enable the cathodic reaction to consume the electrons generated during the anodic dissolution of the metal. Normally, the ferrous ions (Fe^{2+}) and the hydroxyl ions (OH) combine to form ferrous hydroxide, $Fe(OH)_2$, which is subsequently oxidised to ferric hydroxide, $Fe(OH)_3$. This is the basic component of hydrated rust, although other metal oxides and salts such as sulphates may also be present in varying quantities. The physical characteristics of rust are such that it has a light, friable, brittle, non-adherent nature and repeatedly spalls away from the metal surface as brown powder. Accordingly, rust provides little or no protection and the process of rusting just goes on and on, its rate dependent upon the environment to which the iron or steel is exposed.

There are various types of corrosion, which are now discussed.

Atmospheric Corrosion : In the interior of most buildings and

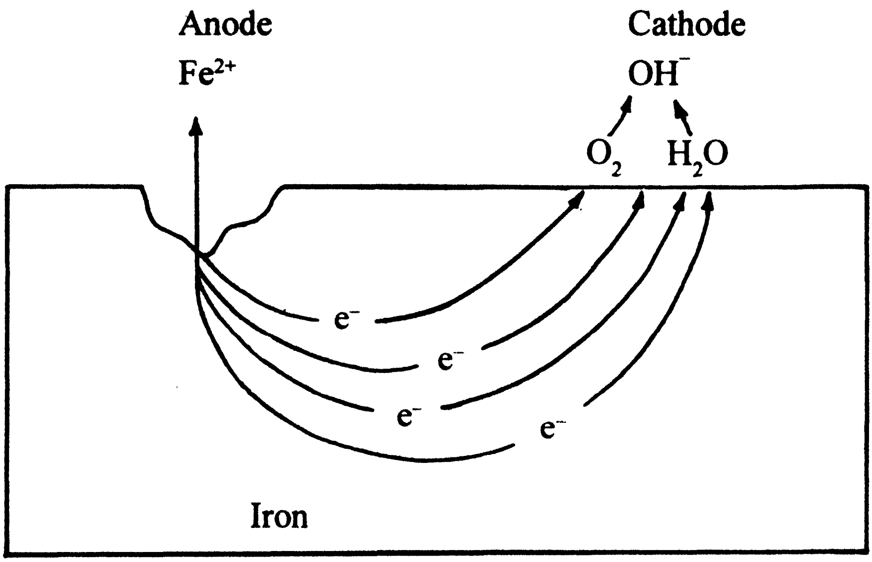

Fig. 14: The electrochemical cell set up between anodic and cathodic sites on an iron surface undergoing corrosion

Plate 8: Bulbous base of the Pillar showing corrosion effects and weld lines due to hammer forging

in clean, pollution-free rural areas the rate of corrosion of iron and steel is very low when the relative humidity is less than 60 per cent. However, rusting is accelerated as the time of wetness increases and as the air becomes contaminated with industrial pollutants or, in marine locations, chlorides. Although the naturally occurring chloride salts—the best known of them is common salt (NaCl) used in cooking—are usually neutral, they are highly conducting and assist the electrochemical reactions involved in corrosion. In addition, compounds such as sodium chloride, just referred to, are hygroscopic or moisture-absorbing and thus can cause rusting at low relative humidities. The most damaging industrial pollutant is sulphur dioxide (SO_2) which reacts with moisture to produce dilute sulphurous acid and sulphuric acid (H_2SO_3 and H_2SO_4) solutions, known as acid rain.

Typical rates of corrosion for normal (i.e., unalloyed) iron and steel in rural, industrial and marine locations are given in Table 8. It is interesting to note that there is a wide variation in corrosion rates in different atmospheres and that Delhi records one of the lowest corrosion rates. However, with the population (and, consequently, the number of vehicles) of Delhi growing rapidly and also with the large-scale development of industries, the situation may well change for the worse in the coming decades.

Fresh Water Corrosion : As in the case of air, the chemical composition and microstructural features of different types of iron and steel have little effect on corrosion rates in fresh water. Even the addition of *small* amounts of copper, chromium and nickel do not have the beneficial effects observed during atmospheric exposure. However, the water composition or purity is of great importance, and the corrosion rates depend on factors such as conductivity, acidity, alkalinity, hardness, type and amount of dissolved solids, organic matter and gases, particularly oxygen. For these reasons, it is very difficult to assign a typical corrosion rate for iron and steel in fresh water, but 40 microns per year is generally accepted as a reasonable rate of corrosion for iron and steel in unpolluted, but oxygenated fresh water. It is relevant to note, and this is not often realized, that this rate of corrosion is

no greater than the atmospheric corrosion in a temperate climate (see Table 8).

Table 8 : Atmospheric corrosion rates for iron and steel (1 mm = 1000 microns)

Sl. No.	Type of environment	Site	Corrosion rate (in microns per year)
1.	Rural (very dry & clean)	Khartoum, Sudan	3
2.	**Rural/Urban very dry**	**Delhi, India**	**8**
3.	Rural (temperate)	Godalming, UK	48
4.	Suburban	Berlin, Germany	53
5.	Urban	Teddington, UK	70
6.	Marine (rural)	Sandy Hood, USA	84
7.	Industrial (in land)	Pittsburgh, USA	109
8.	Industrial (marine)	Corgella, South Africa	114
9.	Heavy industrial	Sheffield, UK	135
10.	Marine (tropical surf)	Lagos, Nigeria	619

Corrosion of iron and steel can be virtually prevented by making the water alkaline artificially. Corrosion can also be brought down if the rust is not removed from the metal surface by the entrainment of hard-water salts in heated systems. Conversely, continuous exposure of bare metal to erosion or abrasion in fast-flowing water containing solid particles will greatly increase the rate of corrosion of iron and steel. Brackish waters have a high conductivity, which accelerates corrosion, while polluted waters with low dissolved oxygen contents are less aggressive, unless microbial attack by sulphate-reducing bacteria is present.

***Seawater Corrosion*:** The rate of corrosion of iron and steel in

seawater is again affected very little by metal composition and microstructure. Such a rate is, in fact, remarkably constant around the world as the open sea has a similar composition, whatever its location on the globe. Even temperature has little effect on immersed iron and steel because the increased rate of the corrosion reaction at higher temperatures is offset by the reduced solubility of oxygen, which depresses corrosion rates. Of course, local coastal factors, such as pollution, can greatly alter the extent of rusting, but the main variable in seawater corrosion is the position of the metal with respect to the water line.

In the fully immersed condition a typical corrosion rate for iron and steel is 50 microns per year, which is only slightly greater than that observed in fresh water. The highest corrosion rate of 100-200 microns per year is recorded at the so-called splash zone where the water is highly oxygenated and the wave action prevents any protective rust film from being formed. Above the splash zone and in the inter-tidal zone the corrosion is slower, decreasing rather rapidly to the normal marine atmospheric rate and the fully immersed rate, respectively.

Soil Corrosion : Soils are complex and their aggressiveness is determined by factors such as retained wetness, oxygen content, dissolved salts, hydrogen ion concentration (the so-called pH value, which is 7 for neutral environments, more for alkaline and less for acidic environments) and organic matter content. Minor variations in the composition of iron and steel are again inconsequential. Oxygen-free soils, such as river beds and sea beds, produce virtually no corrosion, in any case not more than 20 microns per year, even when water-logged. Generally, the extent of rusting in undisturbed soils is very low, much lower than atmospheric corrosion rates, and deep-driven steel piles are known to have remarkably long lives.

Galvanic Corrosion : As described earlier, the so-called anodic and cathodic reactions occur simultaneously on a metal surface, leading to corrosion. In fact, these reactions permit the concept of an electrochemical cell with electrons moving from the anode to the cathodic sites, thereby carrying an electric

current, infinitesimally small though it may be. The sites where the anodic and cathodic reactions take place, i.e., the anodes and cathodes of the electrochemical corrosion cell, are determined by many factors. Firstly, they need not be fixed in location; they can be adjacent or widely separated. Variations over the surface of oxygen concentration in the environment can result in the establishment of an anode at those sites exposed to the environment having the lower oxygen content. Here the corrosion is caused by differential aeration. Similar effects can occur because of variation in the concentration of metal ions or other species in the environment. These variations may well arise because of the position or orientation of the corroding metal. For example, a vertical metal surface can suffer corrosion because gravity can affect the concentration of certain environmental species near its bottom. Finally, variations in the homogeneity of the metal surface due to the presence of inclusions, slags, different phases, grain boundaries, disturbed metal and variation in internal stress levels, can lead to the establishment of anodic and cathodic sites.

When two or more metals or alloys get electrically coupled in the same electrolyte (or electrically conducting solution), the rate of attack on one metal or alloy which is more active or anodic is usually accelerated while the corrosion rate of the other, less active or cathodic, is decreased. This phenomenon is known as "galvanic corrosion" and has led to the arrangement of metals in a galvanic series, with the noble, less active metals at one end and the base, more active metals at the other. The driving force for galvanic corrosion is the potential difference between the component metals in accordance with values of their relative potentials as measured in a particular electrolyte, say seawater (see Table 9).

From a popular point of view, the top metals in Table 9 are the ever-bright, non-corrosive and attractive metals greatly in demand for jewellery, decorations, medallions and so on. As a thumb rule, the greater the separation between two metals in the galvanic series, the greater the corrosion effects on the baser or more active metal.

Table 9 : Galvanic series of some metals and alloys in seawater

NOBLE/INACTIVE END

Platinum
Gold
Silver
Stainless Steel (304 & 316)
Nickel
Bronzes
Copper
Brasses
Tin
Lead
Lead-Tin Solder
Cast Irons
Steels
Cadmium
Aluminium
Zinc
Magnesium

BASE/ ACTIVE END

Prevention of Corrosion

A proper understanding and appreciation of the foregoing principles underlying corrosion processes have naturally led to a number of corrosion-prevention and corrosion-control measures, the more important of which can be classified as follows:

1) ***Corrosion-resistant alloys*** : These alloys contain constituents, such as chromium, which produces an effective, adherent, self-healing, protective oxide film that resists breakdown of the protective layer and repairs itself rapidly.

2) ***Protective coatings*** : In this case, an artificial barrier is applied to the corrosive environment in the form of a uniform coating on the metal surface. The most widely used artificial barriers are organic coatings

(paints, lacquers, waxes and greases), metallic coatings which provide a protective barrier (such as electroplate chromium) or corrode sacrificially (such as zinc in galvanized steels) and ceramic coatings (porcelain, enamels and glasses) that are chemically resistant.

3) ***Cathodic protection*** : Here, corrosion control is achieved by making the structure to be protected the cathode of a galvanic or corrosion cell.

4) ***Corrosion inhibitors*** : This protection scheme seeks to alter the environment to a metal and make it less corrosive, if not altogether non-corrosive, by adding suitable chemicals, the so-called corrosion inhibitors.

In case of iron and steel, the common methods of minimizing rust formation rely on stifling the cathodic reaction that leads to the formation of hydroxyl ions (OH^-). In enclosed places, rusting in air can be prevented by reducing the relative humidity to less than 60 per cent by airconditioning and by minimizing atmospheric pollution. For aqueous environments, such as cooling systems, dissolved inhibitors such as potassium chromate, sodium nitrite and sodium benzoate are used and have proved particularly effective in closed recirculating systems. Another very effective method is to remove the oxygen from the water by deaeration and chemical means in industrial plants such as boiler feed water systems.

If the cathodic reaction cannot be suppressed by the removal of water or oxygen, then the anodic dissolution reaction can be prevented by forcing electrons (e^-) into the iron or steel by providing cathodic protection. This can be done by electrically connecting the structure to a more active metal, such as zinc, or by impressing a direct current, by which the iron or steel is made the cathode, the inert anode being a corrosion-resistant metal, such as platinized titanium. Such cathodic protection can only be provided in the presence of an electrolyte and is, therefore, used in the case of submerged or buried structures.

The other common method of corrosion prevention is to isolate the iron or steel from the environment by means of organic or metal coatings, as already referred to.

Present State of the Pillar

Although the astonishing corrosion resistance of the main, exposed, cylindrical part of the massive Iron Pillar has rightly attracted world-wide attention, it is relevant to record here that the bulbous base (see Plate 8) and the grooved capital of the Pillar have, in fact, been subjected to corrosion effects just like normal varieties of wrought iron. This fact has often not been highlighted in accounts and articles devoted to the Iron Pillar.

It was only in 1961, as mentioned in Chapter I, that the famous Pillar was dug out for chemical treatment, preservation and reinstallation on the eve of the Centenary celebrations of the Archaelogical Survey of India. Dr. B.B. Lal, the then Chief Chemist of this organization, was in charge of these operations and has recorded the following conclusion in his report: "An examination of the buried part of the Pillar and the hollow capital surmounting it has amply demonstrated that the iron of the Pillar is vulnerable to rusting like any other specimen of wrought iron."

The first imprsssion obtained in 1961 was that the portion of the Pillar below the earth was "superficially rusted." However, on detailed examination, the buried portion of the Pillar was found covered with thick crusts of rust and, in fact, copious rust scales could be collected, ranging in thickness from a few millimeters (mm) to no less than 15 mm in some portions. Further, the bulbous base of the Pillar was found riddled with numerous cavities and hollows caused by deep corrosion and mineralization of the iron. The samples of rust scales collected from the corroded base of the Pillar and those of the soil adhering to it were subjected to chemical analysis. The composition of the iron sample drawn from the Pillar base was nearly the same as reported earlier for samples taken from the cylindrical, exposed portions of the Pillar. The soil portions were found, not unexpectedly, to be loaded with appreciable quantities of soluble sulphates and chlorides.

An interesting feature, revealed for the first time during the 1961 investigations, was the presence of a sheet of metallic

lead, 99.37 per cent pure and 3 mm thick, wrapped around the bulbous end of the Pillar to a height of about 80 cm. The lead sheet was found to be in an excellent state of preservation and, barring a superficial whitish layer, the whole sheet was almost completely free from corrosion. It was rightly concluded by Dr. Lal during his 1961-1962 studies that most of the damage to the buried part of the Pillar was caused by prolonged galvanic action and corrosion, induced by the juxtaposition of lead and iron within the Pillar, the latter serving as the sacrificial anode and the former as the cathode. The marked corrosion of the Iron Pillar base and the well-preserved survival of the lead sheet are *both* according to expectations of scientists, since iron stands nearer to the base/active end than lead in the Galvanic Series (see Table 9). It is appropriate to record here in passing that if a zinc sheet had been used in place of the lead sheet, the former would have become the sacrificial anode and corroded, saving the iron of the Pillar from eletrolytic corrosion, even though the rusting of iron would have gone on in the ambient environment characterized by moisture containing dissolved oxygen.

Incidentally, the excavation of 1961 also revealed that the Iron Pillar had a flat circular base with eight thick projections sticking out uniformly around its circumference and overlay an iron grid laid horizontally on a heavy slab of stone resting on a stone foundation. The lead sheet was wrapped all around the foundation to a height of about 80 cm, coming upto just below the Pillar base. The visible lower portion of the Pillar presents a somewhat rough, unfinished and pitted surface, and could well have been embedded in the ground at its original location.

In 1961, the capital of the Pillar with its deep rectangular groove or slot, presumably meant for holding the flagstaff, was also examined to assess its state of preservation. It was found that thick laminated rust scales mixed with earthy matter had accumulated at the base of the groove, indicating considerable corrosion. Evidently, accumulation of rain water as well as sand, dust and clay particles brought by the winds had countributed to marked rusting here over the years. Since the rain water could accumulate to a depth of over a foot in the slot along with dust, the

wetted portions provided rather ideal conditions for corrosion over long spells.

For the effective conservation of the Iron Pillar for posterity, some special measures were undertaken in 1961 on an urgent basis. The preliminary treatment comprised the elimination of the rust, earthy accretions and water-soluble salts, as also rust-preventive treatment, including consolidation of the holes, cracks and cavities. The entire Pillar from the capital to the base was subjected to chemical cleaning for elimination of superficial accretions of oily and sand-clayey matter, corrosion residues, rust stains, etc., before going in for rust-prevention treatment. Before reinstallation of the Pillar, Dr. Lal made the valuable suggestion that a zinc sheet should replace the lead sheet as cover. However, this proposal did not find favour with the structural conservators and archaelogical engineers, who found the available lead sheet handy enough for protecting the Pillar base from direct contact with mortar and saline soil. It can only be hoped that when the Pillar is again set in the new masonry at a future date, the lead sheet will be discarded in favour of a zinc sheet.

Reasons for Corrosion Resistance

The excellent state of preservation of the massive shaft of the Iron Pillar at Delhi despite exposure for over 15 centuries to sun, rain, wind and dust has naturally attracted the attention of modern metallurgists, materials scientists and corrosion technologists. Among the numerous publications dealing with this fascinating phenomenon, some research papers and reviews which appeared over the last three decades deserve special attention and, in fact, constitute the basis for the critical scientific analysis that follows. These valuable contributions are due to Ghosh (1963), Bardgett and Stanners (1963), Lahiri *et al.* (1989), Wranglen (1969 & 1970), Rao (1989 & 1991), Lal (1989), Bindal *et al.* (1989), Dubey (1990) and Biswas (1991). Although interesting and useful in some ways, the earlier studies and reports on the "rustless wonder" are not important any more in the light of the comprehensive scientific investigations of the last thirty years based on equipment, expertise and technological infrastructure far

superior to those of earlier decades. It is relevant to record here, even at the risk of repetition, that Indian scientists have made valuable contributions and rubbed shoulders with Western investigators on a footing of equality during this recent period of enhanced activity in what has proved a rather challenging area of metallurgical research.

The foremost point to be kept in mind here is the extraordinary *inhomogeneity* of the Iron Pillar from many points of view. The Pillar was obviously forge-welded (see Chapter IV) from a great many sponge iron lumps of different compositions, so that the chemical analysis and, consequently, microstructure as well as mechanical properties are *variable* from layer to layer. In the unetched condition, i.e., before etching by acidic solutions to reveal the metallic grain and phase structure, microscopic examination of the Pillar iron reveals slag particles distributed irregularly. In the etched condition the microstructure shows polyhedral grains of ferrite (i.e., almost pure iron) with some slip bands. It also shows small but varying amounts of pearlite (the well-known and intimate mechanical mixture of ferrite and iron carbide, Fe_3C, called cementite in metallurgical terminology). The carbon content thus varies from very low (<0.1 per cent to 0.3 per cent), while the microhardness varies on the Brinell Scale from 80 for pure ferrite to 180 for pure pearlite.

Effect of Chemical Composition : The *average* composition (in weight per cent) of the material in the Pillar may be given as in Table 10.

The variation in *carbon* content has been referred to earlier, but a related point to be stressed is that the carbon percentage is *not particularly low*, as often taken for granted in earlier publications. The carbon content and the volume of pearlite are both lower in the surface layers and increase inwards in the direction of the pillar axis, apparently as a result of surface decarburization (loss of carbon) during hammer-forging of the hot, pasty iron.

Table 10: Average composition of the Pillar material (in weight per cent).

Carbon	.. ..	0.15
Phosphorus	.. ..	0.25
Sulphur	.. ..	0.005
Silicon	.. ..	0.05
Manganese	.. ..	0.05
Nickel	.. ..	0.05
Copper	.. ..	0.03
Nitrogen	.. ..	0.02
IRON	.. ..	Balance

The *phosphorus* content of the Pillar iron is definitely quite high and less varying than the carbon content. It occurs partly as a solid solution (i.e., dissolved) in ferrite and partly as a slag inclusion of iron phosphate ($FePO_4$). Further, the strongly oxidized parts and the surface layers of the Pillar, depleted of carbon, tend to be richer in phosphorus than the interior parts. In a sample containing 0.28 per cent phosphorus, careful analysis showed that 0.18 per cent was dissolved as elemental P in ferrite, whereas the remainder appeared as phosphate slag. It is generally agreed that this high phosphorus content in the Pillar iron checks its corrosion and makes its own distinct contribution to the corrosion resistance of the Pillar. The view of experts has been that in oxygen-consuming corrosion phenomena, as in water and humid atmospheres, phosphorus in ferrite exerts a beneficial influence through oxidation to phosphate which as an inhibitor promotes the formation of protective, impervious oxide films on the Pillar surface.

The *sulphur* content of the Delhi Pillar is very low, according to all analyses, probably because charcoal was used in reducing the ore. Coupled with the fact that the *manganese* content of the Pillar is also very low, the very low percentage of sulphur means that there are very few centres of iron-rich manganese sulphide (MnS) to initiate pit corrosion by serving as

effective local cathodes. In fact, the sulphur printing technique has rarely revealed the presence of any microscopically visible inclusions of sulphides in the Pillar iron. Thus, the low sulphur and manganese contents are expected to make some contribution to the increase in corrosion resistance of the Delhi Pillar.

In terms of modern metallurgical practice, and with particular reference to steel technology, the Pillar iron roughly corresponds to the commercial construction steel En 3 or AISI 1015 of the semi-killed quality. However, the ancient Delhi steel differs from its modern counterpart in the following ways, i.e., it has a:

(1) higher phosphorus content (about 5 times more than in the modern steel);

(2) lower manganese content, often nil, as compared to about 0.5 per cent in the modern steel;

(3) lower sulphur content, almost one-tenth of or even less than that of the modern steel; and

(4) higher slag content and a greater heterogeneity of the same in the than modern steel.

As summed up by Wranglen in 1970, "without being particularly remarkable, the composition of the wrought iron of the Delhi Pillar is favourable for a good corrosion resistance in the atmosphere".

Effects of Protective Films: Many investigators have attributed the Iron Pillar's apparent rustlessness to protective layers or films formed on the surface during its fabrication and/or its long exposure to the Delhi atmosphere. In this context, many theories have been put forward, which need careful study and analysis.

As any visitor will immediately notice, there is a prominent band on the circumference of the Pillar at a height of about 1.0 to

1.5 metres above the stone platform, which is exceptionally bright and smooth, as if specially polished. This is due to the custom of visitors standing with their backs towards the Pillar and trying to clasp their hands around it "for luck." As in the case of the 2000-year old iron chain in a shrine on Adam's Peak in Sri Lanka, frequent contact with human hands, resulting in consequent repeated polishing and greasing, has practically prevented rusting of this portion of the Pillar.

In fact, various studies have established beyond doubt that the Iron Pillar is coated by a protective film varying in thickness from 60 to 600 microns (1 mm = 1000 microns). According to magnetic measurements this predominantly oxide film is less than 50 microns thick in the bright, polished section referred to earlier; it increases to as much as 500-600 microns away from this section. If the oxide film is scraped off, the exposed iron starts to rust, and after a few years the newly formed oxide film cannot be distinguished from the main oxide of the Pillar. There is thus strong support for the theory that the good state of preservation of the Pillar is mainly, if not solely, due to a protective film of corrosion-resistant products.

According to optical, X-ray and chemical investigations, the protective film on the Delhi Pillar seems to consist mainly of Fe_3O_4, which is magnetic as opposed to the non-magnetic $Fe_2O_3.nH_2O$. One analysis gives the following break-up of oxides:

Oxides	(in per cent)
Fe_3O_4	67.0
FeO	13.1
H_2O	14.8
$FePO_4$	1.7
SiO_2	3.2
MgO	0.2
CaO	0.1

The much larger proportion of the magnetic fraction present in the Pillar rust, as compared to the non-magnetic fraction, is a unique feature. In the commonly encountered rust of ordinary mild steel, there is a much greater portion of the non-magnetic oxide compared to the magnetic variety. Evidently under the atmospheric conditions prevailing in Delhi, the rust of the Pillar has not fully undergone further oxidation from the Fe_3O_4 to the Fe_2O_3 stage. It is noteworthy here that the thick rust layers obtained *below the ground* display compositions closer to $Fe_2O_3.nH_2O$.

The phosphate content of the surface oxide film corresponds to 0.35 per cent P in the iron, which is within the variation limits for the analytical P values. However, there is a general enrichment of P in the rust, as compared to the substrate. Experts believe that the portion of P of the basis material, which is evenly distributed in solid solution in ferrite, probably contributes more to the formation of the protective surface film than the heterogeneously distributed inclusions of phosphate slag.

The silica (SiO_2) content of the surface oxide film is much higher than the corresponding silicon content in the pillar iron. Since, furthermore, X-ray studies of the surface oxide reveal the presence of quartz (another form of silica), it is fairly obvious that the SiO_2 content is mainly derived from occluded dust, a direct consequence of the sandstorms (*aandhies*) quite common in and around Delhi; especially during summer. The small quantities of magnesium and calcium oxides (MgO and CaO) on the surface may be traced to the same source.

Incidentally, it is well-known that the thickness of protective films increases according to the parabolic law. On the basic of an initial growth rate of 5 microns/year, the growth over 1600 years works out to be around 200 microns, in good agreement with the average of measured values.

There has been another view put forward by experts to explain the presence of the protective oxide layer on the exposed

portion of the Iron Pillar. In all probability, in the fabrication of this massive Pillar, the technique of hammer-forging hot metal lumps in a pasty condition was employed. To achieve a smooth surface and a well-rounded shape, the hammering must have been heavy, prolonged and systematic. The oxide film formed under these unusual working conditions must have been hammered on to the surface and the slag also must have been driven into the surface. Thus, an adherent, protective layer on the surface of the Pillar would have been formed and this layer would have developed further during the cooling process following the hammering.

The literature on the Iron Pillar contains many references to indigenous formulations and oil-anointing rituals to protect it from atmospheric corrosion. These make interesting reading, but such practices cannot be easily evaluated on a modern scientific basis.

Environmental Effects : According to some experts, the deciding factor behind the rustlessness of the Iron Pillar at Delhi has been the comparatively dry climate and the relative unpolluted environment of the Delhi area, particularly over the 15 centuries up to the beginning of this century. As summarized in Fig.15 the climatic conditions at Delhi have some special features contributing to low corrosion rates for irons and steels. The most important of them is the low Relative Humidity (R.H.) of the air at Delhi, as at many other hot and dry places in the world. It is only in morning hours during the monsoon rains in July, August and September and also sometimes in January that the R.H. exceeds the critical value of 70 per cent, above which noticeable rusting starts. In the afternoons the R.H. never exceeds this critical limit. In fact, the R.H. is very low (20-40 per cent) except during the monsoon period.

Delhi is no desert. In fact, the rainfall is considerable, amounting to about 700 mm per annum, as in many parts of Europe, even though this amount of rain may be considered relatively small for a country like India. This rainfall in conjunction with the generally high temperatures (see Fig. 15) contributes to

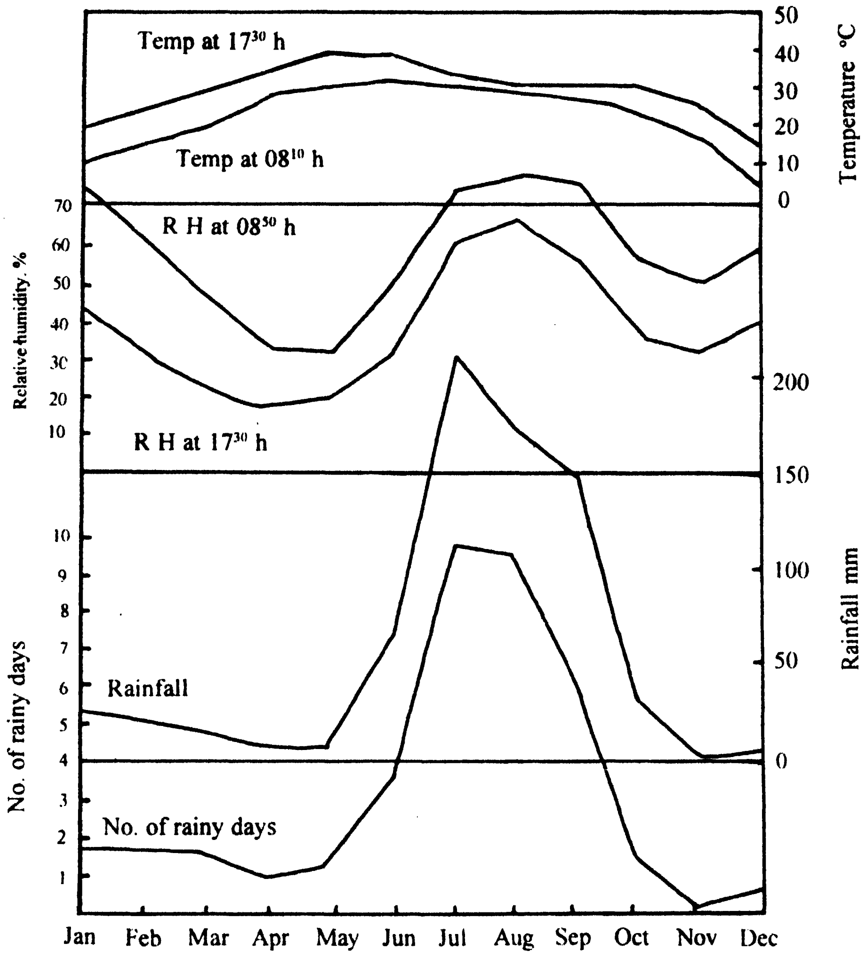

Fig. 15: Diagrams showing detials of the climate at Delhi

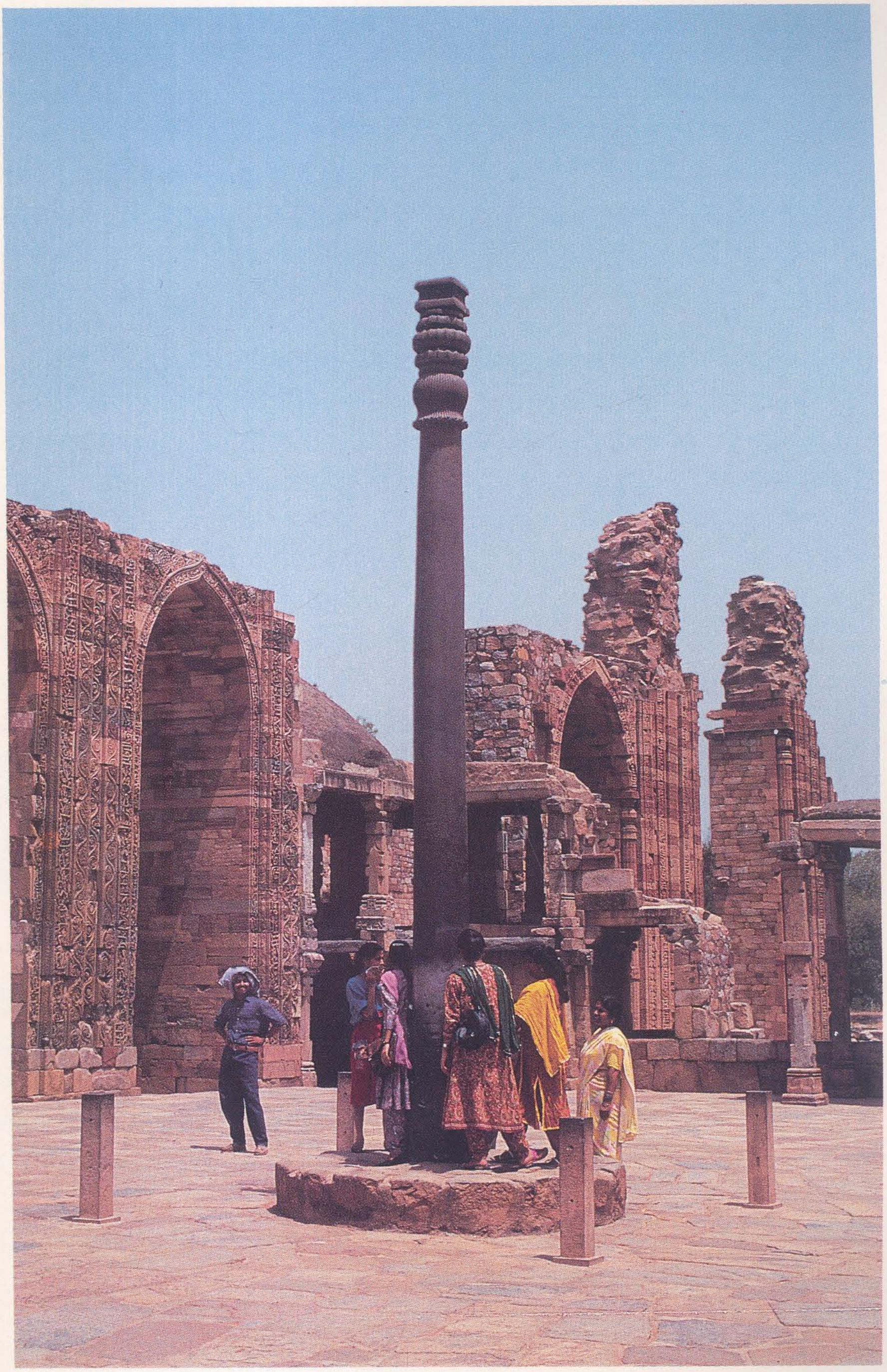

Plate 9: The Pillar surrounded by tourists -- an every-day phenomenon

the dry climate, in which moisture readily evaporates. This is particularly true of a large, freely-exposed object of considerable heat capacity such as the six-tonne Iron Pillar. As can be appreciated even by laymen, the heavy Pillar absorbs large quantities of solar radiated heat. This counteracts dew precipitation during the night and results in rapid drying after rainfall. It is also to be noted here in passing that the heavy monsoon rains also exert a rinsing and cleansing effect on the Pillar.

In such a discussion on the influence of climatic factors on corrosion phenomena, the pollution of the atmosphere cannot be forgotten. Due to small-scale industrialization and little use of fossil fuels, the concentration of corroding gases such as sulphur dioxide (SO_2) is rather low in most parts of India. Accumulation of waste products from animals and human beings, generating ammonia, will persumably indicate for a hot and densely populated country like India that the atmosphere is generally *alkaline* rather than *acidic* and hence conducive to good corrosion resistance in irons and steels. Conditions have been changing fast in India since independence in 1947 and particularly due to the rapid industrialization of the last three decades, but the conditions outlined here can be held valid for the last 15 centuries for areas in and around Delhi.

An important general observation made in 1960 by U.R. Evans, (the English pioneer in the then emerging discipline of corrosion science), is relevant to our present discussion. With regard to *all* old iron structures built during the ancient or the medieval age and preserved in good condition today, the following two factors have to be kept in mind according to Evans:

(i) The atmosphere under rural conditions prevailing during the early exposure of metallic objects was much less corrosive than now, and might even have been passivating (i.e., inhibiting corrosion) due to an excess of ammonia from dunghills, cowsheds, stables, etc. The initial conditions of exposure often determine the life of a metal in the atmosphere and, under favourable conditions, a protective

layer of corrosion products is formed that protects the metal even when the atmosphere becomes more polluted.

(ii) It is worthwhile to note that only those metals survive which have the most favourable compositions and conditions to resist corrosion. Other and less corrosion-resistant maerials disappear with the efflux of time and are not any more available for examination.

Effects of heterogeneity along with slag inclusions : The lack of homogeneity in chemical composition, and hence in microstructure, as also in the distribution of non-metalic phases like slag inclusions, oxide particles etc., in the Pillar iron has been well documented by several investigators. The inhomogeneity has also been rightly attributed to the forge-welding technique which was applied to numerous lumps or balls of hot pasty iron over a period of time to shape this unusual Pillar. However, due consideration has so far not been given to the possible favourable role of this multi-faceted heterogeneity in protecting this Pillar from atmospheric corrosion.

The occurrence of galvanic corrosion has been discussed earlier in this chapter. One type of such corrosion is the so-called intergranular corrosion caused by metallic impurities segregating at grain boundaries and serving as cathodic sites in corrosive environments to the detriment of the metal or alloy forming the grains. This phenomenon is labelled as "intergranular" because it proceeds *along* the continuous network of grain boundaries. In case of the Delhi Pillar, the progress of such intergranular corrosion may well be halted effectively by non-metallic barriers such as slag inclusions, oxide particles etc., segregated at the grain boundaries.

The hammer-forging technique used to join together hot iron balls produced in different "heats" (i.e., reduction processes) has introduced, not surprisingly, non-uninformities in chemical composition, microstructure and work hardening of the grains, along with imperfections like slip bands and inclusions like those of slag and oxides, in the Delhi Pillar. All these heterogeneities

may be expected to contribude in some measure to the remarkable corrosion resistance of this Iron Pillar. This is because in general terms any metallurgical process proceeds smoothly and rapidly in a uniform, homogeneous material, but gets halted, hindered or slowed down by heterogeneities like imperfections, non-metallic obstacles etc. Even a continuing process such as corrosion may be stopped offectively by microscopic or even sub-microscopic entities that break the smooth homogeneity of the concerned material.

Most recently, based on studies undertaken at the Indian Institute of Technology, Kanpur, it has been proposed by Balasubramaniam that slag particles play a highly beneficial role in providing corrosion resistance to the forge-welded Delhi Pillar. Invoking the mixed potential theory postulated in 1938 by the German scientists Wagner and Traud, Balasubramaniam has suggested that the enhanced cathodic reduction reactions due to the presence of slag. particles at the grain boundaries can lead to the formation of a passive protective film of phosphate, possibly in a glassy or amorphous state, conferring thereby high corrosion resistance to the Pillar. Experimental support for this concept has been provided by electrochemical potêntiodynamic studies on 700 year-old Indian iron, with and without slag inclusions.

* * *

EPILOGUE

Many important conclusions have been reached in the foregoing chapters on several fascinating as well as intriguing aspects of the famous Iron Pillar located in the outskirts of Delhi. The time has now come to sum them up all together and to show that the Pillar need not be looked upon anymore as a myth or a mystery or an enigma. It has definitely stood out as a marvel of its age from a technological point of view and will remain so for all time to come.

A survey of the relevant literature makes it clear that the Delhi Pillar (see Plate 9) has been attracting, for well over a century and a half now, the admiration of antiquarians as well as the curiosity of scientists and technologists, particularly metallurgists, mainly because of its large size and excellent state of preservation. Not surprisingly, it has been a star attraction of Delhi for tourists coming not only from all countries of the Indian subcontinent, but also from distant parts of the world.

In his authoritative book *A History of Indian and Eastern Architecture,* James Ferguson made the following observations as early as in 1910 about the Iron Pillar:

> Taking 400 A.D. as a mean date... and it certainly is not far from the truth.... this Pillar opens our eyes to an unsuspected state of affairs to find the Hindus at that age capable of forging a bar of iron larger than any that have (sic) been forged even in Europe up to a very late date, and not frequently even now... It is almost equally startling to find that, after exposure to wind and rain for fourteen centuries, it is unrusted, and the capital and inscriptions are as clear and as sharp now as when put up fifteen centuries ago.

Some three decades later, Jawaharlal Nehru, who later became independent India's first Prime Minister and was always known for his critical and unbiased approach to world history, wrote in his popular book *The Discovery of India*:

> Apparently ancient India had made great progress in the working of Iron. In New Delhi there towers a great Iron Pillar which baffles contemporary scientists. They cannot determine the method of manufacture which prevented the iron from oxidation and other atmospheric hazards.

In the long section on "History of Metallurgy," forming part of the eight-volume *Encyclopedia of Materials Science and Engineering* (published in 1986 by Pergamon Press), there is the following reference to the Delhi Pillar:

> In India, the Iron Age appears to have arrived at about the same time as in China. While the overall results were possibly not as spectacular, the iron pillar at Delhi (6.7 m above ground and 0.5 m below ground, tapering from 420 mm diameter to 320 mm at the top, the whole weighing 6 tonnes) and at Dhar (now broken, but probably originally twice as high as the Delhi Pillar and, although more slender, weighing about 7 tonnes) call for comment. Both seem to have been made by the same procedure of welding together innumerable small bloomery products; they are quite staggering pieces of engineering for their dates.

It is not surprising that the *metallurgical* world was particularly impressed by this unique Pillar. In 1947, as India became a free nation and the Indian Institute of Metals was established, the Iron Pillar became the obvious choice for its emblem.

The sense of pride in the ancient monument has been demonstrated by scientists and scholars of independent India on many an occasion, particularly in seminars and conferences devoted to Indian science and technology. When the permanent exhibition grounds were established at the spacious Pragati Maidan in New Delhi a few decades ago, the Government of

India decided to instal an exact replica of this famous Iron Pillar in a prominent place there to inform and inspire visitors to the exhibitions.

Date of the Iron Pillar

The clear six-line Sanskrit inscription in the *Gupta -Brāhmi* script on the Iron Pillar has always been the starting point in determining the date of this massive metallic monument. On the grounds of palaeograhy, content, language, style of writing and so on, scholars, both from Europe and India, have been in general agreement in assigning the earlier part of the Gupta period. i.e., *late fourth century to early fifth century*, say *A.D. 370 to A.D. 430*, to the Iron Pillar. The only controversy has been in regard to the identification of the king referred to in the *praśasti* (eulogy) inscribed on the Pillar, the choice narrowing down even here to Samudra Gupta and Chandra Gupta II (Vikramāditya) who ruled over their respective empires from A.D. 340 to A.D. 376 and A.D. 376 to A.D. 414 respectively.

Since the *praśasti* in the *Gupta-Brāhmi* script is definitely posthumous, on the basis of internal evidence, it follows that, in all probability, it was got composed and engraved on the Pillar by the grateful son of a great warrior-king, the choice of the son thus zeroing in on Chandra Gupta II or his son Kumara Gupta I whose reign is supposed to have flourished between A.D. 414 and A.D. 455. Going by the Sanskrit text of the eulogy, the Iron Pillar is a *dhwaja-stambha* (symbolic flagstaff) installed originally in a Vishṇu Temple by a royal devotee of Lord Vishṇu. This devotee was also a mighty conqueror and an empire builder, who acquired sole and supreme sovereignty over vast areas of the Indian subcontinent, extending his domain even to the southern ocean, *by his own prowess*. The only king who answers to this description adequately is Samudra Gupta and hence the Pillar should have been erected during the last stages of his long and eventful reign i.e., close to A.D. 375. The three Sanskrit *ślokas* (verses) that constitute the six clearly engraved lines on the Pillar thus go naturally with the very early years, i.e., close to A.D. 380, of the reign

of Chandra Gupta II, the grateful inheritor of a vast empire from a great soldier and conqueror, the Vikramāditya who patronized scholars and poets most generously and appreciatively.

Thus the conclusion here may be stated as follows:

1. Date of erection of the Pillar : circa A.D. 370-375
2. Date of inscription of the Pillar : circa A.D. 380-385

Mode of Fabrication of the Iron Pillar

To appreciate the problems involved in making and shaping iron, a survey of the global scene is helpful, with due consideration being given to the advent of the Iron Age around 1500 B.C., perhaps, in Asia Minor, the gradual spread of the "bloomery process" to several parts of Asia and Europe, the introduction of the "blast furnace" in Italy in the fifteenth century A.D. and the revolutionary advances in large-scale steel- making in Western Europe during the last century. As far as the Indian sub-continent is concerned, the Iron Age seems to have made its appearance in several places around 1300-1200 B.C. and the Indian megalithic culture during the period 1200 B.C. to A.D. 200 seems to have been closely associated with the use of iron and application of Indian versions of the "bloomery process" which were capable of producing iron in batches of tens of kilograms through the reduction of iron ore by charcoal.

Scientific studies of the Iron Pillar during the last over thirty years, wherein Indian scientists and technologists could join hands effectively with their European counterparts, have thrown much light on the technology that went into the making of this massive metallic monument well over 1500 years ago. The following facts have emerged from recent non-destructive, microscopic, X-ray, chemical and mechanical testing of this Pillar as well as the so-called *Ādivāsi* (primitive) iron samples from later dates:

1) The Pillar iron is heterogeneous in composition and structure, rather like most *Ādivasi* iron samples.

2) The composition of the Pillar iron is comparable to that of a low-carbon steel.

3) While manganese is virtually absent, the phosphorus con tent is high in the Pillar iron.

4) The visible weld lines, the marks due to strong hammering, the oxide film incorporating the slag and the non-uniformity in composition strongly suggest that the Pillar was forge-welded quite ingeniously and effectively, starting with lumps of hot, pasty iron mixed with slag.

5) There is no evidence of melting and subsequent solidifica tion of the Pillar iron, i.e., the latter was never in the liquid state.

6) Traditional blacksmiths of Aligarh have suggested on their own in 1924 such a hammer-forging and welding process involving "pancakes" of hot iron for fabricating a pillar of this size.

Thus, the conculusion of modern-day metallurgists on the mode of fabrication of the Pillar is as follows: The Iron Pillar at Delhi was not cast in one piece, but fabricated ingeniously by forging and hammer-welding lumps of balls of hot pasty iron in a step-by-step process.

Reasons for the Iron Pillar's Rustlessness

No other aspect or characteristic of the Delhi Pillar has attracted such worldwide attention as the corrosion resistance of its cylindrical exposed portion. This unusual and rather baffling phenomenon of rustlessness during over 15 centuries of exposure to sun, rain and winds cannot, however, be associated with the bulbous base below the ground or the grooved capital on top of this massive Pillar.

Detailed scientific investigations over the last 30 years, mostly

at Indian laboratories, have brought out several features of the Pillar iron and its environment, each of which may have a bearing on the apparent rustlessness associated with this ancient monument.

Firstly, the low-carbon iron of the Pillar is characterized by high phosphorus, low sulphur, low manganese and high slag contents, apart from considerable inhomogeneity in the microstructure. All these features can contribute individually and collectively to good corrosion resistance in respect to atmospheric factors.

Secondly, the Pillar is coated with a complex protective film varying in thickness from about 50 microns in the bright polished section handled by visitors to a maximum of about 600 microns away from this bright section on either side. This film is rather unique in composition with about 67 per cent Fe_3O_4, the magnetic oxide of iron, only 13 per cent FeO, nearly 2 per cent $FePO_4$ and around 3 per cent SiO_2. This adherent protective layer with some slag driven into it during the heavy hammer-forging that went into the shaping of this massive, cylindrical monument has definitely made its contribution to the unusual corrosion resistance exhibited by the Pillar over the centuries.

Thirdly, the climatic conditions in Delhi, marked by low humidity of the air and reasonably high day temperatures for most part of the year, leading to considerable heat absorption and consequent prevention of dew precipitation as well as rapid drying after rainfall have made a definite contribution to the unusual rustlessness exhibited by the Pillar. The comparative lack of industrial pollution thus far in the area near the Pillar and the proaouncedly alkaline rather than acidic nature of the Indian rural environment could also have enhanced the corrosion resistance of the Pillar.

Lastly, the non-uniformity in microstructure characterized by slag inclusions, particularly at the grain boundaries, and structural imperfections such as slip bands and microstrains, is likely to

prevent intergranular corrosion and generally hinder progress of the corrosion processes.

Thus, the results of different scientfic studies point to several factors viz., unusual chemical composition, adherent protective film, comparatively dry and unpolluted climatic conditions and microstructural heterogeneities, contributing collectively to the phenomenal corrosion resistance of the cylindrical exposed portion of the Iron Pillar at Delhi.

* * *

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